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INVESTIGATION OF LONG TERM EXPOSURE EFFECTS UNDER STRESS ON SUPERSONIC TRANSPORT STRUCTURAL MATERIALS

(PHASE I REPORT)

PREPARED BY

METALLIC MATERIALS LABORATORY

APPROVED BY

N. Klimmek

N. KLIMMEK, Director
Research Laboratories

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FOREWORD

The appended report is the result of studies carried out under Contract NASW 746 for NASA Headquarters, Washington D. C. It covers the first phase of a 30,000 hours stress corrosion test and work done in the period of June 1963 to July 1964.

Title: Investigation of long term exposure effects under stress of supersonic transport structural materials.

Author: Dr. George Martin

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DESCRIPTIVE TERMS

Corrosion
Stress Corrosion
Titanium Alloys
PH Steels
Superalloys
Long Term Exposure
Brazing Alloys
Elevated Temperature Exposure

INVESTIGATION OF LONG TERM EXPOSURE EFFECTS UNDER STRESS ON SUPERSONIC TRANSPORT STRUCTURAL ALLOYS

Geo. Martin

Prepared under Contract No. NASw 746 by
NORTH AMERICAN AVIATION, INC.
Los Angeles Division, Los Angeles, Calif.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

The report covers the first phase of a 30,000 hours exposure test. Six materials - two titanium alloys, two PH steels and two superalloys - were tested under stress in five environmental conditions comprising combinations of salt and braze coatings and constant and cyclic exposure at 650 F. Braze coated titanium alloys, salt coated Titanium 8Al-1V-1Mo alloy and cyclically exposed AM 350 M steel were the only alloys subject to stress corrosion failure within the 15,000 hours exposure covered. In this period relative phase changes occurred in the titanium alloys without significant mechanical property changes and aging reactions occurred in both steels and the superalloys with appropriate mechanical property changes. A hypothesis for corrosion reactions on titanium alloys in salt environments has been developed.

Author

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SUMMARY

This report describes the results of the first phase of an investigation of the metallurgical and mechanical property changes occurring in six candidate materials for supersonic transport vehicles on exposure to 650 F in the stressed and unstressed condition under various surface environmental coatings. The first phase consisted in the examination of specimens exposed for 10,000 and 15,000 hours and specimens which have failed by stress corrosion within that period.

The six candidate alloys tested were two titanium alloys, two precipitation hardening steels and two superalloys. The specimens, in the shape of cantilever strips loaded to stress levels varying from 23% to 90% of the yield stress, were exposed to a temperature of 650°F. Surface treatments consisted of salt coatings, braze coatings and salt coated braze coating and cyclic exposure at 650°F and a humidity cabinet.

After a period up to 15,000 hours, most of the braze coated and braze coated plus salt coated titanium alloys have fractured by stress corrosion. In addition, two out of six salt coated titanium 8-1-1 alloy specimens and two out of six of salt coated AM 350 M alloy specimens have failed. Four out of four AM 350 M alloy specimens exposed to a cyclic environment of furnace temperature and humidity cabinet failed, all after approximately 3,000 hours.

The mechanical tests indicate that all alloys except the steels are affected by the braze alloys. The titanium alloys are strongly affected. Steels and superalloys undergo aging reactions during the exposure period, which affects both the strength levels and the ductility. Stress during exposure did not appear to affect any of the changes in mechanical properties observed. No gross changes in metallurgical structure of any of the alloys could be observed. X-ray diffraction studies, however, do indicate changes in the relative amounts of alpha and beta phase after exposure of the titanium alloys.

Stress corrosion fractures are of a typical intercrystalline nature in both the titanium alloys and the AM 350 alloys. Neither microscopic nor electron microscopic replica studies have so far indicated any structural change directly related to the corrosion mechanism. However, examination of fractured titanium alloy specimens by means of an electron microprobe indicate evidence of segregation of heavy alloying constituents near the crack.

The corrosion products on titanium specimens exposed under coatings of natural and artificial sea salt have been examined by X-ray diffraction and there appears to be tentative evidence for the existence of NaOH formed during the exposure process. Thermodynamic calculations show the feasibility of several reactions resulting in this product.

INTRODUCTION

The Institutions responsible for material selection for hi-speed aircraft designed for long time service, such as the National Aeronautical and Space Administration, the Federal Aviation Agency and the Aerospace Industry,have for considerable time been keenly aware of the problems involved in the selection of materials for such aircraft. Materials required for such aircraft are either radically new families which have to be developed and evaluated or they consist of known materials exposed to a new type of environment. Materials likely to be of prime importance are titanium alloys, hi-strength steels and superalloys. Most of those materials must be heat treated to develop suitable properties. However, such properties can only be obtained in what are basically meta-stable metallurgical structures. It is a matter of concern whether long time exposure to elevated temperatures with or without stress would lead to changes of such meta-stable structures and therefore to changes in the mechanical properties. In addition to this standard type of information,such as the strength of the various temperature levels, creep data and fatigue information, a very high degree of assurance is required that the materials chosen will not be subject to a sudden type of failure such as stress corrosion. The environments likely to lead to stress corrosion are braze coatings, which may have been used for joining and particularly the possibility of sea salt incrustation covering the external surfaces of the aircraft. It is estimated that the type of aircraft considered here may be exposed on the external surfaces to temperatures up to 650 F during the service life in excess of 30,000 hours. Complex interactions between the coatings, the temperature and any structural changes appearing in the material after long time elevated temperature exposure can therefore be expected.

A general program to determine the likelihood of a stress corrosion failure in appropriate candidate materials was started by North American Aviation, Inc., in 1962. The present program consists of a comprehensive evaluation of specimens with a failed by stress corrosion or remained exposed to periods of 10,000 and 15,000 hours. This program was aimed at the determination of any possible degradation in mechanical properties,at a search for evidence of possible changes in the metallurgical structures and at an evaluation of a possible reaction involved in stress erosion. The specimens exposed under the program organized by North American Aviation, Inc., were to form the basis of information. Specific tests carried out include notched and unnotched tensile tests, microscopic examination, examination of the metallurgical structure by electron-microscope replication, X-ray diffraction studies of possible phase changes, and also examination of surface products with a view to a better understanding of corrosion and stress corrosion mechanisms. The entire program is planned to investigate the effects on materials of a total exposure time of 30,000 hours.

This report covers the first phase of the investigation. The second phase will deal with 20,000 hour exposure effects and a final third phase will deal with materials after 30,000 exposure. The design of the experiment, that is the number and type of specimens chosen, is such that at the completion of 30,000 hour investigation, all test results will be available in duplicate.

SURVEY OF PREVIOUS WORK ON

STRESS CORROSION

The susceptibility of titanium alloys to stress corrosion cracking when in intimate contact with sodium chloride at elevated temperatures has been known for many years. The limits of the corrosion reaction were not known nor was the corrosion mechanism established, although many theories have been proposed.

Evidence (reference 1) had established that titanium alloys are subject to stress corrosion cracking when in intimate contact with sodium chloride at temperatures above 500 F. No service failures were reported (to mid-1957) which were attributed to this type of corrosion. Laboratory tests had shown that various coatings (oxide films, anodic films, aluminum and nickel metallic coatings) would mitigate this type of corrosion. The limits of the corrosion reaction were not known nor was the corrosion mechanism established, although various theories have been proposed. Further studies were recommended to identify the corrosion product, establish differences between types of titanium alloys, and the effect of salt concentration and thickness of salt coatings. A theory of the corrosion mechanism was advanced which suggests that titanium in the presence of oxygen and a reducible chloride forms $TiCl_2$. Sodium chloride was established as a crack nucleating agent. It was shown that moving air across the specimen surfaces during corrosion exposure increases the resistance of the material to stress corrosion. Glass bead peening and a sodium hydroxide anodizing treatment were demonstrated to afford protection against stress corrosion of Ti 6Al-4V alloy.

Apart from salt, three other environments were found to stress corrode titanium; (reference 2) these were molten cadmium, red fuming nitric acid (RFNA), and hydrochloric acid formed by the decomposition of a chlorinated diphenyl compound in air at 600 F. The molten cadmium corrosion occurred on a Ti 4Mo-4Al alloy in contact with a cadmium-plated bolt at 600-750 F. Stress corrosion cracking of Ti 5Al-2.4 Sn alloy was found to take place in the presence of halides (trichloroethylene) during heat treatment at temperatures of 1150 F and 1500 F for 16 hours (reference 3). Severe cracking, other than stress corrosion cracking, was also found to occur with stress present if a surface oxide coating was present. This effect accentuated any difficulty encountered by halide contamination.

Ti 6Al-4V and Ti 8Al-1Mo-1V were incapable of withstanding an exposure of 25,000 psi at 650 F for 1000 hours, but Ti 8-1-1 did not fail at 450 F. Discusses possible corrosion mechanisms involving gaseous chlorine attach and also galvanic corrosion. Tests conducted to investigate electro-chemical corrosion mechanism. Exposure of notch titanium specimens in a 650 F sea salt environment prior to stressing at 25 KSI was found to prolong specimen life (reference 4). Stress corrosion cracks were found in Ti 8Al-1Mo-1V specimens in which sea salt had been packed into a notch consisting of a 1/16 inch diameter hole in the center of a sheet specimen and the specimens then exposed at 650 F and stresses of 25 and 63 KSI for 50 and 200 hours, respectively, and at 800 F and 25 KSI for 100 hours (reference 5). Materials Research Laboratory reported evidence that Ti 6Al-4V alloy stress corrosion in hot salt is electrolytic in nature, with the titanium becoming anodic to chloride ions in a postulated thin film of eutectic or low-melting salts. In this hypothesis free chlorine does not enter directly into the corrosion mechanism and is not essential to it. Titanium alloys Ti 6Al-4V and Ti 8Al-1Mo-1V exhibit stress corrosion failures at 700 F and above, but not at 600 F (reference 6).

As far as other SST alloys are concerned, data are less conflicting than those for titanium. The superalloys (Inconel W and cobalt-base V-36 alloy) were unaffected by heavy coatings of dry sea salt when exposed at 40,000 psi for 1000 hours at 650 F and 850 F (Inconel W only). AM 350, CR20 was also unaffected at 650 F (reference 4).

Similar specimens of AM 350 CR and PH15-7Mo RH1050 did not exhibit any cracking after exposures at 650 F and 800 F and stresses of 40 and 70 KSI for up to 1000 hours, and at 650 F and 100 KSI stress for 1000 hours (reference 5). Douglas Aircraft Company tests show that AM 350 SCT 850 is quite susceptible to stress corrosion under beach exposure and salt spray testing. PH15-7Mo RH1100 is apparently not susceptible to stress corrosion testing at room temperature but becomes susceptible after 1000 hours exposure at 650 F. Superalloys have not shown any stress corrosion defects through 1000 hour alternate immersion and 100 hour beach exposure. Lockheed Aircraft Corporation reported that AM 350 SCT 850 with an "optimum chemistry" showed good resistance to stress corrosion in marine environment, but that AM 350 SCT 850 with an "unfavorable chemistry" was considered relatively susceptible (reference 6).

EXPERIMENTAL PROCEDURE

Six materials were chosen for investigation. Two titanium alloys, Titanium 6A-4V and Ti 8Al-1Mo-1V appeared to be the most likely titanium alloy candidate material. PH15-7Mo steel and AM 350 steel were selected to represent the whole family of age hardening meta-stable austentite stainless steels. Superalloys selected were Rene' 41 and Inconel 718. Analysis of the various alloys as well as their heat treat condition and mechanical properties as determined by standard tensile specimen are shown in Table 1. It should be noted that Ti 8Al-1V-1Mo used for the experiment had been subjected to a single solution treatment because at the time of commencement of the investigation, the advantages of the duplex annealing process of that alloy had not yet been discovered.

Materials selected were in the form of sheet ranging in thickness from .020 to .050 inches. From these sheets, strips approximately 12 inches long and an inch and one-half wide were cut in 12 inch length in the longitudinal rolling direction. The details of the heat treatment used is shown in Table II. All brazing and heat treatment in titanium alloys was carried out in retorts filled with argon in order to minimize contamination. Subsequent to heat treatment, the specimens were machined to dimensions shown in Figure 1. Two types of specimens were prepared. One type of specimen was exposed in the plain sheet form while another specimen was notched in a direction at right angle of the principal axis at two points: one point of slotting was close to the support area while the other point was near the loading points. All specimens were supported at one end in a stainless steel frame, clamped between mica-strips for insulation, and loaded on the other end to produce a cantilever type specimen. This cantilever type specimen was chosen in preference to the usual constant strain U-type stress corrosion specimen. It was considered possible that on the long exposure periods some relaxation in a constant strain type specimen may take place and thus change the stress level. Another advantage of the cantilever type specimen is that a large number of specimens can be accommodated in a limited space. A test involving direct tensile loading would have required an extensive and expensive set up, in order to produce the required stress levels. Cantilever specimen allows direct comparison of stress corrosion effects and corrosion effects, as one end of the specimen is under a condition of maximum stress and the other end is virtually unstressed. The assembly of the specimens in a test frame is indicated in Figure 2, and Figure 3 shows the loaded frame placed in a furnace. A total of six frames each accommodating 24 specimens were available. The heating device chosen was an air circulation type furance equipped with dual control. The air circulation furnace is run constantly, except for two periods of breakdowns. During those breakdown periods, the specimens remained untouched and loaded, but at room temperature.

Each of the six materials tested was exposed with a variety of five different surface conditions or surface treatments. These conditions are summarized in Table III. Prior to all surface treatments strict attention was paid to cleanliness of specimen surfaces. All surface grease and stains had been carefully removed by a degreasing and pickling treatment and no handling of specimens after this treatment with bare hands was permitted. The surface treatments were applied as follows:

(a) Exposure in as received condition except for surface cleaning and pickling treatments.

(b) Specimens prepared as above, and subsequently coated by brushing with a suspension in water of synthetic sea salt comprising 6 parts sodium chloride and one part magnesium chloride. This suspension was brushed on and after drying resulted in an even coating of approximately 1/32 of an inch thickness.

(c) Specimens prepared as (a) above and one coated with a coating .001 to .003 inches thick of a braze material considered suitable and likely at the time of the commencement of test. Braze coatings were selected from the following brazing alloys:

Titanium Alloys:
Dynabraze B. (94.8% Silver, 5% Aluminum, 0.2% Manganese)

Steel and Superalloys:
Premabraze 130 (72% Gold, 6% Chromium, 22% Nickel)

(d) Specimens prepared as (c) above but coated subsequently with a salt coating as under (b)

(e) Specimens prepared as under (d) above but exposed cyclically by maintaining them in the furnace at exposure temperature for a fortnight, then removing the frame into a humidity cabinet for exposure in water saturated air at 100 F for a fortnight, followed by return to the furnace for a fortnight's exposure and so on.

Suspension weights were machined from stainless steel and connected through the specimens by means of stainless steel wire and small insulating bead. In this manner, accidental electric contact between weights frame and different specimens was minimized. During exposure in the furnace the air circulation caused a small oscillators movement of all specimens. This was not considered significant, as this small movement extending to perhaps .050 inches on either of the equilibrium conditions would not produce significant changes in the stress levels. The frame taken out for cyclic treatments at fortnightly intervals was handled as gently as possible, but a certain amount of joggling could not be avoided. Furthermore, it was found that after the two years exposures, the specimens became coated with a certain amount of dust, particularly brick dust from furnace flues. These vibrations, jolts, and dust coatings therefore do constitute an unknown environmental factor. However, it is not considered that this factor was very significant. In addition to the regular thermocouples forming part of the furnace equipment and operating controlling mechanisms, temperature checks were carried out at three separate instances. Fur the purpose of these temperature checks, six thermocouples were distributed at various points inside the furnace and the temperatures measured by means of a potentiometer. In all cases, the thermal temperature variation in the furnace was found to be plus 0 minus 20 degrees as that indicated by the regular furnace thermometer. A slight temperature drop was indicated near the furnace door, this leak could not be sealed completely. Furnace atmosphere can thus be assumed to be fairly static, although a certain admixture of fresh air did take place.

The size of the weight loading the specimens was selected such that two series of stress levels was obtained. In the plain specimens the maximum stress level was 25 to 30 percent approximately, in the notched specimens a stress level approaching the yield stress was achieved, theoretically at least, at the bottom of the notch. Stress levels are summarized in Table IV for each type of material, and for each type of exposure, both for the notched and the unnotched specimens. Actually stress levels in individual specimens had to be calculated using the theory of beams with large deflections. The general method of calculation and equations involved are given in Appendix A. A computed program was developed to allow the calculation for each specimen for each level arm length and for each specimen thickness. The results of these calculations are given in Tables V to X for each specimen. The Tables also show the stress concentration factors which were assumed for the notched specimen. Appendix A also gives a method of calculation of stress levels at position intermediate between the point of load support and the point of specimen support.

At fracture or at any indication of the specimen obtaining a permanent bent both the specimen and portion held within the clamp were removed from the furnace and stored for further examination. These specimens together with one specimen for each material and set of surface conditions removed after 10,000 and 15,000 hours were then cut up for further examination. Details of method of sectioning of specimens is shown in Figure 4. The pieces of both ends are reserved for microscopic, electro-microscopic and X-ray investigations. The section adjacent to the edge of the supporting beam and adjacent to the hold carrying the weight was used for notched and unnotched tensile specimen testing. Each specimen provided a total of two notched and two unnotched tensile test specimens. As the original test strips were all cut in the longitudinal rolling direction, the tensile specimens therefore represent the transverse properties.

Considerable trouble was experienced in the design of a suitable tensile specimen. This was due to the fact that the total tensile specimen lengths were limited by the one and one-half inch width of the exposure strip, while extensometer with the shortest available guage length required a one-half inch length. One purpose of cutting tensile specimens in the transverse direction as indicated was to assure that the stress distribution across the tensile specimen would be virtually constant. Had the tensile specimens been cut the same direction as the strip lengths, then the stress during exposure would have varied appreciably across the tensile specimen gauge length. A number of specimen design configurations and specimen holding grips were tried and discarded after it was found that specimens either tended to slip or break in the grip. It was essential to use a pinned type tensile specimen, because the rough surface, after the exposure, made friction grips quite unreliable. The final specimen configurations are shown in Figure 5, and the types of grips are shown in Figure 6. A complete set up showing specimen, grips, and extensometer is shown in Figure 7.

EXPOSURE EFFECTS ON METALLURGICAL STRUCTURE

Metallurgical Examinations

Cross sections of all specimens were examined just prior to exposure and after 10,000 and 15,000 hour exposure or failure. During examination particular attention was paid to the top surface of the specimens. In the case of specimens which had failed due to stress corrosion failure, sections were also taken in the plane of the specimen across the cracked zone. After completion of microscopic examination, electron microscopic examination was carried out by means of two stage replicas. Replicas were prepared from the etched micro-specimen surface in the usual manner. A collodion replica was made of the surface which was then shadowed with carbon. After dissolving away the collodion, the carbon copy was placed on the specimen holder of a Hitachi HU-11 electronmicroscope and examined. All microscopic examinations were carried out at a magnification of 500, and electron-microscopic examinations were reproduced at magnifications of 2,500 and 15,000 times.

Titanium 6Al-4V Alloy

The structure of the alloy prior to exposure is shown in Figure 8. The microstructure shows the typical alpha beta phase distribution. There is very little evidence of surface contamination. Some of the grain boundaries near the surface in photomicrograph are somewhat heavier than in the body of the material. The structure is resolved further in the electronmicroscopes shown below the photomicrograph. The metallurgical structure after 10,000 and 15,000 hours is shown in Figure 9. There is definite evidence on this photomicrograph of the grain size and the grain shapes. In the 15,000 hour case some coagulation of the light etching phase into larger grains has resulted. This observation is borne out by the electron micrographs which quite distinctly show coagulation of the light etching phase after the 15,000 hour exposure.

Titanium 8Al-1Mo-1A Alloy

Figure 10 indicates the structure prior to exposure. Comparing this structure to the structure of an uncoated specimen exposed to 15,000 hours, shown in Figure 11, it appears that there is no significant change in the structure, which consists primarily of the alpha phase.

PH15-7Mo Steel

Neither photomicrographs nor electron-micrographs indicate any apparent changes in the metallurgical structure. Figure 12 shows the structure prior to exposure. Figure 13 structures after 10,000 and 15,000 hours of exposure. The distribution of austenite and Martensite phases appears to be unchanged. There is no indication of any widening of grain boundaries nor is there any indication of the appearance or disappearance of any precipitates. There is, however, a slight indication of possible change in the Martensite structure on exposure. A high magnification electron-micrograph shows a fairly coarse Martensite structure prior to exposure which after 10,000 and 15,000 hours is progressively refined.

AM 350 M Steel

AM 350 steel exhibited definite change in the fine structure. Figure 14 shows unexposed structure which can compare to Figure 15 showing the 15,000 hours structure. A most significant change is a loss of fine structure in the Martensite grains. There is no evidence of austenite stringers in any way disappearing or interfering with stress corrosion cracking. Electron-micrograph indicates some absorption of intergrannular precipitates after exposure.

Inconel 718 Alloy

No major changes in the structure of Inconel 718 alloy after exposure are indicated, as can be seen by comparison of Figures 16 and 17. There is,however, a slight indication of the absorption of some of the intergrannular precipitates both from the photomicrographs and electro-micrographs and also an indication of a coarsening of the precipitation hardening phase. There is some indication of of precipitate coagulating in the grain boundary areas, particulary as indicated by the electron-micrographs.

Rene' 41 Alloy

Microstructurally Rene' 41 shows no gross structural changes after exposure up to 15,000 hours. The surface structure effect in this alloy, where the grain boundaries tend to disappear near a free surface, is typical of this alloy and found in all specimens. Electronmicrograph show an absorption of a precipitate phase after exposure both in 2,500 and 15,000 magnification electron-micrographs. There also appears to be an absorption of grain boundary precipitates on prolonged exposure.

X-Ray Diffraction Analysis

Samples of all specimens were examined by X-ray diffraction in the unexposed condition and after 10,000 and 15,000 hours exposure. In the case of the titanium 6Al-4V alloy, diffraction patterns indicate that the beta phase is retained up to 10,000 hours and then tends to diminish. In titanium 8Al-1V-1Mo alloy, however, approximately 50% of the original amount of beta phase is removed in the first 10,000 hours, after which the amount of beta tends to stabilize. In PH15-7Mo steel the amount of retained austenite tends to diminish progressively, but does not disappear after 15,000 hours exposure. AM 350 M steel contains a small amount of retained austenite only, which appears to be stable. No changes were noticed in the superalloys. The diffraction patterns obtained allow only a qualitative comparison of the various amounts of phases existing. Work was commenced on the determination of the actual cell sizes, from which more absolute quantitative data could be obtained, but this work has not been completed.

CHANGES IN MECHANICAL PROPERTIES

Mechanical properties as exemplified by the ultimate strength, the yield strength and the elongation for the case of unnotched tensile test specimens and by the ultimate tensile strength in the case of notched tensile specimens were determined on all specimens removed from the test after 10,000 hours and after 15,000 hours and on all specimens which fractured prior to the 15,000 hour period, in a manner described above. Each exposure specimen thus yielded two tensile specimens, one from the stressed and one from the unstressed portion of exposure specimen. Data are therefore given for the unnotched and notched tensile properties for the stressed and unstressed condition. For the purpose of analysis, each material will be considered separately.

When considering the tensile data, the fact that all specimens tested are cut in the direction transverse to the direction of rolling and the curve of the specimen must be borne in mind. Apart from the anisotropy due to rolling direction, the test direction employed eliminates the effect on strength of any minute edge cracks due to corrosion. Due to the bend curvature of the exposure specimen such cracks are most likely to be in the direction transverse to the length of the exposure specimens, i.e. parallel to the direction of tensile load in the tensile test specimens. A clear distinction can therefore be made between the effects of uncontrolled and un-measurable corrosion surface deterioration and true material property changes. It is felt that in materials subject to excessive corrosion, stress corrosion failures would occur within the test period and thus point up the need for a protective coating.

A comparison has been made between the results obtained from the miniature specimens employed and standard tensile test specimens. As the data in tables show, there is very little difference in the test results, and the test results obtained on the miniature specimens can therefore be considered to be quite representative.

In the case of braze coated specimens, no special allowance has been made for the lower strength of the thin layers of braze alloy. Braze alloy thickness is of the order of 0.001 inch to 0.002 inch maximum and all braze coated specimens have a thickness of 0.040 to 0.50 inches. Braze alloy strength is of the order of 30,000 psi. The total error introduced by not considering the fact that braze coated specimens do in fact represent a composite beam in tension is therefore of the order of approximately 2% only.

Titanium 6Al-4V Alloy

Test results are given in Table XI and shown diagramatically in Figures 20 and 21. There does not appear to be any significant difference in the properties of the material exposed in the stressed and the unstressed condition. Strength levels of materials exposed without braze coatings do not vary significantly except for the case of 10,000 hours exposure of the stressed specimens, which appear to have a lower strength in the as treated surface condition. There is an indication of an increase in the ductility after exposure as shown by the elongation. Braze coated specimens, exposed both with and without a salt coating, have a significantly lower strength and ductility, although there is considerable scatter of data.

The notched/unnotched tensile strength ratio appears to be little affected by exposure time and remains above unity for the type of notched specimen used.

Titanium 8Al-1V-1Mo Alloy

This alloy exhibits a stress behavior similar to the other titanium alloy above, except that the salt coated specimens, too, exhibit a loss in strength on exposure. Ductility losses on exposure appear to be less pronounced than those of titanium 6Al-4V alloy. The embrittling effect of braze coating is considerable and appears to increase with time. Both notched and unnotched tensile strength are similar, indicating no significant change in notch toughness. Test data are given in Table XII and are summarized in Figures 22 and 23.

PH15-7Mo Steel

Relevant data are shown in Table XIII and illustrated in Figures 24 and 25. The mechanical property determinations of the alloy indicate quite clearly that the aging process is continuing during the first 15,000 hours exposure. Both stressed and unstressed specimens exhibit similar behavior. The unnotched tensile properties show that there appears to be an aging peak after approximately 10,000 hours exposure. However, the fact that both the cyclically and the continuously exposed specimens show similar properties indicates that the aging peak occurs somewhere prior to the 10,000 hour exposure level, because the cyclically exposed specimens actually only spent 5,000 hours at elevated temperature. The aging peak is accompanied by a loss in ductility and a loss in notched tensile strength, as compared with the ultimate strength of the unnotched specimens. This decrease in the notched/unnotched tensile ratio is improved after prolonged exposure to 15,000 hours, but does not reach the ratio of the unexposed material. The effect of the aging process on mechanical properties can be considered to be quite significant from a design point of view. There is also a considerable spread of test results, especially in the case of notched tensile date after 10,000 hours, for the different surface treatments.

AM 350 M Steel

The results of the test data are shown in Table XIV and in Figures 26 and 27. Like the PH15-7Mo steel, this material too undergoes an overaging process during the 15,000 hours exposure period. The spread of the test results, however, is wide and it is more difficult to draw definite conclusions at this stage from the available data. It appears that the aging peak occurs somewhere before 10,000 hours in the braze coated specimens, but is in excess of 15,000 hours in the other specimens. Notched tensile data, too, indicate a braze coating effect. The possibility of a component of the braze alloy diffusing into the steel and changing the precipitation reaction can therefore not be excluded. This material did exhibit stress corrosion failures and the test data on the failed specimens are somewhat lower than on the specimens which have not failed, particularly with regard to ductility. Notched/unnotched tensile ratios are around unity in all cases, except for the case of braze coated specimens after 10,000 hours exposure, where they are significantly below unity.

Inconel 718

The test data given in Table XV and drawn in Figures 28 and 29 show that this material undergoes an aging process, without, however, reaching a strength peak. The aging process appears to be stress insensitive. There is some spread of data, particularly at the 10,000 hour level, with the braze coated specimen persistently showing the lowest results. The notched/unnotched tensile ratio remains around unity for all conditions and exposure periods.

Rene' 41

Test data are shown in Table XVI and Figures 30 and 31. Several observations appear to be significant. The material undergoes an aging reaction with a peak strength somewhere before the 10,000 period. This aging reaction is not connected with a reduction in ductility or notched strength, both of which appear to increase on the average. There is no stress sensitivity in any property. The aging reaction appears to be affected considerably by the braze coating. The notched/unnotched tensile ratio is considerably below unity for all cases of surface treatment and exposures, being worst at the aging peak and approaching unity after prolonged exposure.

CORROSION AND STRESS CORROSION EFFECTS

General Surface Corrosion Effects

Specimens exposed in the furnace atmosphere were examined several times each week for fractures and bending. Specimen frames (except the one carrying specimens undergoing cyclic exposure) were removed from the furnace for a thorough examination at five intervals only, after 2800 hours, 4,700 hours, 8,900 hours, 10,000 hours and 15,000 hours exposure. The surface appearance of the various specimens for the different surface treatments is summarized in Tables XVII to XX. The surface appearances after 10,000 hours were substantially similar to the appearance after 8900 hours exposure and details on examination after 10,000 hours have therefore not been reproduced separately.

A photograph of typical surface appearances is shown in Figure 32. The photograph indicates the main observations made on the various surfaces:

(1) Titanium alloys without braze coatings form white areas on a predominantly blackground. These areas are either in spots or stringers.

(2) Braze coatings on titanium alloys tends to flake off completely after even a few thousand hours exposure. The surface beneath the flakes is coarse crystalline in appearance and very rough.

(3) Precipitation headening steels are attacked if salt coatings are present. Particularly heavy was the attack on AM 350 M exposed under cyclic conditions.

(4) Uncoated specimens suffer discoloration only.

(5) Superalloys exhibited the greatest resistance to corrosion under all conditions.

Stress Corrosion Fractures

Of the six materials exposed, only three materials have so far shown any evidence of stress corrosion. These are the two titanium alloys and AM 350. Figure 33 summarizes the total number of failures found. In titanium 6Al-4V alloy only the braze coated specimens were prone to failure. No failures have been found in salt coated or cyclically exposed specimens of this alloy.

Titanium 8-1-1 alloy is likewise prone to stress corrosion failure after braze coating, with or without salt; and failures of this alloy have also been found in two salt coated specimens. Failure of AM 350 steel after cyclic exposure occurred following significantly closely-related failure periods. Of four specimens exposed, all failed after 3,000 hours ± 10%. None of the other materials have so far failed in stress corrosion.

Stress Corrosion Mechanism

In addition to a study of direct stress corrosion failure data and the changes in mechanical and metallurgical properties on exposure, the present study also aims at an attempt to obtain more information on the stress corrosion mechanisms involved. To further this aim, both vertical and horizontal sections through cracked specimens were prepared and examined by means of both the conventional microscope and the electron microscope, using replica techniques for the latter. These studies were supported by X-ray diffraction studies of the corrosion products, particularly on titanium alloys, and by electron microprobe studies of the areas immediately adjacent to the cracks.

The results of the metallographic investigations are shown in Figures 34 to 41. Very strong evidence of surface corrosion is exhibited in the braze coated specimens. Figure 34 shows the cross section through two braze coated specimens of titanium 6Al-4V alloy which failed after 7,124 hours and 15,000 hours exposure respectively. A photomicrograph shows evidence of an interdiffusion zone between the braze coating and complete disintegration of the grains below that braze coating diffusion interface. Of particular interest is the electron microscope replica of the specimen which failed after 7,124 hours. This replica shows the crack preceding through the alpha-beta grain boundary in most cases, but there are at least two incidences where the crack traverses a grain. The shape of the alpha and beta grains appear to be somewhat altered, possibly due to the results of a diffusion reaction. It should be noted that in this electron microscope replica the border on the top left hand corner is not the specimen surface, but the shadow of the specimen holding grid in the electron microscope. Figure 35 is a microstructure of the specimen which failed after 15,000 hours exposure, sectioned in a plane parallel to the specimen's surface. The fracture is a very typical stress corrosion branch-type of fracture proceeding intergranularly, thru the material. The bottom right hand corner of the specimen indicates cracked zones which are not connected to the surface.

Titanium 8Al-1V-1Mo shows a similar effect to the Titanium 6Al-4V alloy. Figures 36 to 38 show the tendency of cracks to move through the heavy intergranular precipitation zone, although some examples indicate that short cuts of the cracks through grains are possible. Figure 39 shows the structure of a salt coated specimen of titanium 8Al-1V-1Mo alloy, which had not failed after 10,000 hours. It is interesting to note that the structure of this specimen does not indicate any heavy and continuous grain boundary precipitates.

The third material prone to stress corrosion failure was AM 350 M steel. Figure 40 shows the heavy grain boundaries formed and incipient cracks at a section through the surface. Figure 41, the structure of a failed specimen, however, does not indicate any material structural changes which may be responsible for such failures.

Very interesting data were indicated by the X-ray diffraction examination of the corrosion products on titanium alloys. It had generally been assumed that the culprit in the stress corrosion attack of salt on such alloys is the formation of chlorine or titanium chlorides. However, the presence of such chemical products has never been proven. Our X-ray diffraction results show the complete absence of any spectral lines due to the presence of titanium chlorides or sodium titanate, which has also been suggested as a by-product of chloride reactions. One specimen of titanium 8-1-1 alloy, exposed for 15,000 hours with a coating of synthetic sea salt, did indicate positive evidence of the existence of NaCl and MgO, and also showed an additional five lines which have been tentatively identified with NaOH. However, the diffraction pattern was diffuse, which was probably due to particle size distribution. The intensity and spacing of the lines obtained on this sample are summarized in Table XXI. The MgO lines are probably derived from dust contamination originating from the furnace bricks. Another sample of the corrosion products of a specimen exposed to less than 5000 hours was boiled in distilled water in an effort to eliminate the diffuse pattern. In this material a positive identification of anatase (a form of TiO_2) was made, and again three weak lines corresponding to NaOH were found. Now, anatase is the titanium oxide which is preferentially precipitated from alkaline solutions in preference to the more common titanium oxide, rutile.

The thermodynamics of possible chemical reactions of the ingredients present which could result in the formation of NaOH was then studied. One example is the reaction:

$$2\ NaCl + Ti + 1/2\ O_2 + H_2O = TiCl_2 + NaOH$$

The free energy change of that reaction is shown in Figure 42. It must be stressed that the hypothesis that NaOH is actually formed relies on a very few preliminary data, and requires further study for the positive identification of the surface reaction. The possible presence of NaOH could result in the formation of a number of compounds which are liquid at temperatures of 650 F and slightly below. The proof of such a reaction could lead to the establishment of a minimum temperature of stress corrosion susceptibility, corresponding to the lowest melting point of the reaction products.

Electron Microprobe Analysis

In order to gain further insight into the stress corrosion mechanism of titanium, electron microprobe analysis was carried out on sections cut at right angles to the crack in titanium alloy strips which had failed by stress corrosion. Figure 43 shows the results of the examination of titanium 8-1-1 alloy, both in the unexposed condition and also after exposure under a salt coating to failure which occurred after 4000 hours at 650 F. In the sample current image, dark areas indicate concentration of elements with high atomic numbers. In the back scatter images such areas show up light. It can be seen that exposure resulted in a distinct coarsening of the size of the areas containing elements with high atomic numbers, in this case molybdenum. The central areas in the photos relating to the exposed specimens indicate the crack. There is a distinct concentration of elements with high atomic numbers (again molybdenum) in the area adjoining the crack. Analysis of the composition of the light and dark areas gave the following results:

	Backscatter Image	
	Dark Areas	Light Areas
Molybdenum	0.65%	3.25%
Vanadium	0.86%	1.04%
Aluminum	8.52%	7.71%

These analyses are estimated to be accurate to about 2 percent of the amount of the element report. The segregation of molybdenum in local areas was confirmed by a random traverse taken over a distance of about 100 microns, analyzing the Mo K α line with a lithium fluoride crystal.

In titanium 6Al-4V alloy, somewhat similar element segregation phenomena could be observed relating to concentration changes in vanadium and aluminum. Backscatter electron image photographs of the alloy are shown in Figure 44. The sample taken for this investigation (No. AD3K) was a specimen which had been both braze coated and salt coated and had failed by stress corrosion. The electron microprobe measurements were carried out on a transverse section. Corrected analysis results were as follows for the various structural areas:

	% Vanadium	% Aluminum
Bright Areas in Matrix	5.73	6.41
Dark Areas in Matrix	3.12	8.07
Small Crack Area	3.80	10.36
Bright Area in Vicinity of Small Crack	4.79	8.33
Bright Area in Network Region	2.55	8.57
Dark Area in Network Region	3.39	5.40

Tests were also carried out to detect the possible presence of silver (from the brazing alloy) and sodium (from the salt coating). Of the latter, the lower limit of detectability is around 2 percent and none but a possible trace near the edge could be found. Silver was detected qualitatively near the edge and in various locations within the cracks. There was therefore, within the limits of detectability, no evidence of the diffusion of either of these elements into the titanium alloy.

CONCLUSIONS AND RECOMMENDATIONS

The report presents interim results obtained during the first half of a 30,000 hours exposure test. Most conclusions must therefore be considered tentative only and subject to correction and amplification after completion of the test.

1. Of the candidate materials test (titanium 6Al-4V, titanium 8Al-1 Al - 1 Mo, PH15-7Mo steel, AM 350 M steel, Inconel 718, Rene' 41) only the titanium alloys and AM 350 M are subject to stress corrosion failure in the presence of salt on exposure at 650 F and stress levels above approximately 25% of the yield strength.

2. Silver braze coating on titanium alloys cause rapid surface deterioration and there is a complete loss of adhesion between the braze coating and the parent material. Gold base brazing alloy does not appear to affect the corrosion behavior of ferrous and superalloys.

3. All alloys appear to undergo slight changes in the metallurgical structure, which are reflected in the mechanical property changes and possibly also in the stress corrosion behavior.

4. Mechanical properties are changed in precipitation hardening alloys on exposure. The change is most pronounced in precipitation hardening steels, least pronounced in the superalloys.

5. The results on examination of surface films and microprobe tests allow the establishment of a very tentative hypothesis of factors affecting the stress corrosion mechanism of titanium alloys. It appears that this mechanism is related to the formation of NaOH from salt coatings and segregation phenomena in the alloys. Hypothetically, these compositional changes produce local potential differences, which, under the possible presence of a liquid phase containing NaOH, are capable of propagating stress corrosion cracking.

Future work under this program will be concentrated mainly on changes in metallurgical structure and mechanical properties. It is strongly recommended that programs be initiated supplementary to this to:

1. Investigate further the hypothetical stress corrosion mechanism for titanium alloys suggested here. Such an investigation would lead not only to a better understanding of the mechanism, but also to the establishment of guidelines for the development of alloys of improved stress corrosion resistance.

2. Investigate aging effects of various heat treatments on PH steels and superalloys to reduce the effects of elevated temperature exposure on mechanical properties.

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APPENDIX A

STRESSES AND DEFLECTIONS IN CANTILEVER BEAMS

Introduction

Due to the small bending stiffness of many of the cantilever beams relative to the loading, it was necessary to resort to a large deflection theory for this analysis. The material properties at 650°F listed on Table XXII were used for this analysis.

Large Deflection Theory

Figure 45 shows the relation between moment arm and maximum deflection versus a load stiffness index (reference 7). The maximum decrease in lever arm for specimens was found to be about 20%, i.e. from Figure $\frac{L^*-D}{L^*}$ was found to be about .800.

Effective Length of Beams

Figure shows a typical loaded beam. Where P is the applied load, L is the length of the beam from load point to angle support, and L_o is the distance inside the angle to the fixed point of the beam. Since temperature the total length of the cantilever beam can be expressed as

$$L^* = (L_o + L)\,(1 + \alpha\Delta T) \text{ or } L_o = \frac{L^*}{(1 + \alpha\Delta T)} - L \qquad \text{Equation (1)}$$

where:

L^* = total length of beam (in.)
α = coefficient of thermal expansion at 650° (in/in°F)
ΔT = (650°F - 70°F)

For five test beams the δ deflection readings at the load point were recorded.

For each beam, the following procedure was then used to obtain the value of L_o. A value of L^* was assumed and the corresponding value of $P\bar{L}^{*2}/B$ was calculated.

where:

B = EI bending stiffness (# in^2)

I = $\frac{bt^3}{12}$ moment of inertia (in^4)

t = beam thickness (in)

b = beam width (in)

ν = Poisson's ratio

Using this value of PL^{*2}/B and Figure 45, the corresponding value of δ/L^* was found. This value was compared to $(\delta \text{ measured})/L^*$. If the two values were different a new value of L^* was assumed and the process was repeated until δ/L^* from Figure 45 equaled $(\delta \text{ measured})/L^*$. Then, by the use of Equation (1), L_o was calculated. Table gives the values of L_o for the beams on which the deflections were measured. Based on Table XXIII it was decided to make L_o equal to .3 for all test beams. Equation (1) then becomes:

$$L^* = (.3 + L) \quad (1 + 580\alpha) \qquad - \quad \text{Equation (2)}$$

Un-Notched Beams

Using these corrections the maximum deflections and stresses for the un-notched beams here calculated. These calculations are based upon the total thickness of beams and do not take into account the material properties effects of those beams coated with braze alloy. If the actual stress in the braze alloy and parent material are wanted, the following procedure can be used. From the tables, the nominal maximum stress of the specimen can be determined by the following equations:

$$\sigma_{max\ \text{braze alloy}} = \sigma_{max\ \text{nominal}} \frac{\left(1 + \frac{d}{t}\right)^3}{\frac{E_2}{E_1} + \frac{3d}{t} + \frac{3}{}\left(\frac{d}{t}\right)^2 + \left(\frac{d}{t}\right)^3} \qquad \text{Equation (3)}$$

$$\sigma_{max\ \text{parent material}} = \sigma_{max\ \text{braze alloy}} \times \frac{t}{t+d} \times \frac{E_2}{E_1} \qquad \text{Equation (4)}$$

where:

E_1 = Young's modulus of braze alloys
E_2 = Young's modulus of parent material
t = total thickness of parent material
d = total thickness of braze alloy

Notched Specimens

A similar set of calculations was carried out to determine the maximum deflection at the load point and the maximum stress at the interior notch for the notched beams. The corresponding stress concentration factor K_t is also given (Reference 8). These calculations are also based on the nominal thickness of the specimens and exact values of stresses can again be obtained with the use of Equations (3) and (4).

Determination of Stresses in Un-Notched Beams at Intermediate Locations

The stresses at any point intermediate between the support and the point of load application in an un-notched beam can be determined from the following procedure:

a. Obtain the maximum bending stress and load-stiffness index (PL*/B) from the appropriate table.

b. From Figure 46, read the factor $(L - \Delta - X)/(L - \Delta)$ for the appropriate beam position and load stiffness index. Intermediate values of S/L must be interpolated from the curves given.

c. The desired stress is the beam's maximum stress multiplied by the factor obtained from Figure 46 .

TABLE I

CANDIDATE MATERIALS

ALLOY	ANALYSIS %	ANALYSIS %	ANALYSIS %	HEAT TREATMENT	MECHANICAL PROPERTIES F_{TU} 1000 PSI	MECHANICAL PROPERTIES F_{TY} 1000 PSI	MECHANICAL PROPERTIES ELONG % ON 2 IN.
TITANIUM 6 Al-4V	Al 5.98	C .03	Fe .01	STA	161.9	151.2	11
	N .011	O .11	V 3.99		160.9	150.4	12
					159.8	152.3	10
				BRAZE	142	130.5	15
					144	128	13.6
					157	116.5	16.1
TITANIUM 8Al 1 Mo IV	Al 8.43	Mo 1.22	V 0.94	NONE	153.5	143	7.7
					156.5	143	12.8
					152.4	144.2	17.5
					152	143.4	17.5
					150.5	143.6	17.5
				BRAZE	144	138	14
					138	130	14
					138	131	13
PH 15-7 Mo	Al 1.36	C .066	Cr 15.1	RH 1050	204		6
	Mn .53	Mo 2.20	Ni 7.04		203	192.5	5.4
	P .016	S .010	Si .43		204	197	6
AM 350 M	C .010	Cr 16.23	Mn .97	SCT 850	203	165	13.1
	Mo 2.70	Ni 4.23	P .011		201	170	13
	Si .23				202	167	12.5
INCONEL 718	Al .38	C .05	Cb 5.51	STA	189	142	21.5
	Cr 18.26	Cu .09	Fe 17.42		191	143	16
	Mn .26	Mo 3.71	Ni 53.34		190	137	23
	S .007	Si .33	Ti 1.03				
RENÉ 41	Al 1.48	Co 11.48	Cr 18.32	STA	197.5	148.5	13.8
	Fe .13	Mn .04	Mo 10.05		194	147.5	12.8
	Si .05	Ti 2.84			194	146.5	13.5

TABLE II

SUMMARY OF HEAT TREATMENTS

Titanium 6Al-4V	Braze at 1725F air cool unbrazed specimen: Age at 1000F for 4 hours
Titanium 8-1-1	Braze at 1725F air cool unbrazed specimen: no heat treatment
PH 15-7 Mo	Braze at 1900F (brazed specimen only) cool to room temperature heat to 1730 F cool to - 100F, hold 4 hours age at 1075F for 1 hour air cool to room temperature
AM 350M	Braze at 1900F (brazed specimen only) cool to room temperature heat to 1710F, cool to - 100 F, age at 850 F for 3 hours air cool to room temperature
Rene' 41	Braze at 1950 F (Brazed specimen only) air cool to room temperature age at 1400 F for 6 hours air cool to room temperature
Inconel 718	Braze at 1900 F (Brazed specimens only) air cool to room temperature stress relieve at 1600 F for 4 hours air cool to room temperature age at 1325 F for 16 hours air cool to room temperature

TREATMENT	EXPOSURE TEMPERATURE	COATING
A	650°F	NONE
B	650°F	SYNTHETIC SEA SALT
C	650°F	BRAZE COATING TITANIUM ALLOYS: DYNABRAZE B (94.8% Ag, 5% Al, 0.2% Mn) OTHER ALLOYS: PREMABRAZE 128 (72% Au, 6% Cr, 22% Ni)
D	650°F	BRAZE COATING AS ABOVE PLUS SYNTHETIC SEA SALT
E	ALTERNATING FORTNIGHTLY 650°F AND HUMIDITY CABINET AT 100°F	SYNTHETIC SEA SALT

Table III Summary of Surface and Exposure Treatments

NOTCHED SPECIMENS	Ti 6-4	Ti 8-1-1	PH15-7 Mo	AM 350 M	INCO 718	RENE' 41
MAXIMUM SPECIMEN STRESS (KPSI)	44.6/58.0	56.2/66.6	140.6/168.4	129.3/160.3	92.4/105.5	126.8/147.2
% FTY (STD TMT)	34.0/38.4	41.5/46.6	72/86	77.3/96	65.5/74.8	85.6/100
% FTY (BRAZED TMT)	35.8/38	42.2/43.7				

UNNOTCHED SPECIMENS

MAXIMUM SPECIMEN STRESS (KPSI)	23.0/36.8	22.5/31.4	53.7/61.3	50.0/59.1	34.0/40.8	48.8/57.4
% FTY (STD TMT)	22/26.5	19/22	27.5/31.4	30/35.4	24.1/28.9	33/38.9
% FTY (BRAZED TMT)	23/26.5	17/24.1				

NOTE: VARIATIONS BETWEEN SPECIMEN STRESS LEVELS ARE DUE TO DIFFERENCES IN THE FREE LENGTH OF THE CANTILEVER ARM.

Table IV Maximum Stress Levels in Test Specimens

TABLE V - Maximum Stress Levels

Test Material: Titanium 6Al-4V

ENVIRONMENT	SPECIMEN NUMBER	MAX. STRESS psi	K_t
Continuous exposure in circulating air at 650 F	AA1	35,900	
	AA2	35,200	
	AA3	35,600	
	AA4	35,300	
	AA5	59,000	1.895
	AA6	59,000	1.895
	AA7	33,900	
Coated with synthetic sea salt and then continuous exposure in circulating air at 650 F	AB1	33,200	
	AB2	34,200	
	AB3	33,400	
	AB4	32,000	
	AB5	52,500	1.945
	AB6	52,200	1.945
	AB7	33,700	
Coat with brazing alloy and then continuous exposure in circulating air at 650 F	AC1	28,100	
	AC2	28,600	
	AC3	28,900	
	AC5	48,700	1.970
	AC6	48,400	1.975
Coated with brazing alloy plus synthetic sea salt and then continuous exposure in circulating air at 650 F	AD1	32,400	
	AD2	29,300	
	AD3	30,200	
	AD5	45,600	1.992
	AD6	47,800	1.975
Coated with synthetic sea salt, then alternating 14 day exposure in humidity cabinet at 100 F and in circulating air at 650 F	AE1	33,600	
	AE2	32,500	
	AE3	34,200	
	AE4	33,000	
	AE7	33,200	
	AE8	33,700	

TABLE VI - Maximum Stress Levels

Test Material: Titanium 8AL-1V-1Mo

ENVIRONMENT	SPECIMEN NUMBER	MAX. STRESS psi	K_t
Continuous exposure in circulating air at 650 F	BA1	30,300	
	BA2	28,900	
	BA3	30,900	
	BA5	67,600	1.88
	BA6	67,400	1.88
Coated with synthetic sea salt and then continuous exposure in circulating air at 650 F	BB1	26,400	
	BB2	27,700	
	BB3	28,500	
	BB5	61,200	1.885
	BB6	60,700	1.89
Coat with brazing alloy and then continuous exposure in circulating air at 650 F	BC1	25,800	
	BC2	31,000	
	BC3	21,900	
	BC5	59,800	1.895
	BC6	59,900	1.895
Coated with brazing alloy plus synthetic sea salt and then continuous exposure in circulating air at 650 F	BD1	23,800	
	BD2	22,000	
	BD3	24,800	
	BD5	60,400	1.89
	BD6	57,600	1.91
Coated with synthetic sea salt then alternating 14 day exposure in humidity cabinet at 100 F and in circulating air at 650 F	BE1	27,100	
	BE2	27,000	
	BE3	28,900	
	BE4	27,800	

TABLE VII - Maximum Stress Levels

Test Material: PH15-7MO

ENVIRONMENT	SPECIMEN NUMBER	MAX. STRESS psi	K_t
Continuous exposure in circulating air at 650 F	CA1	59,700	
	CA2	58,800	
	CA3	58,200	
	CA4	57,500	
	CA5	165,200	1.735
	CA6	165,200	1.735
	CA7	58,500	
Coated with synthetic sea salt and then continuous exposure in circulating air at 650 F	CB1	55,700	
	CB2	55,600	
	CB3	58,200	
	CB4	58,000	
	CB5	154,200	1.76
	CB6	155,900	1.755
	CB7	58,500	
Coat with brazing alloy and then continuous exposure in circulating air at 650 F	CC1	54,100	
	CC2	52,800	
	CC3	55,500	
	CC4	53,000	
	CC5	146,500	1.78
	CC6	140,300	1.79
	CC7	53,200	
Coated with brazing alloy plus synthetic sea salt and then continuous exposure in circulating air at 650 F	CD1	52,400	
	CD2	52,600	
	CD3	53,700	
	CD4	52,300	
	CD5	146,300	1.781
	CD6	146,400	1.791
	CD7	53,200	
Coated with synthetic sea salt, then alternating 14 day exposure in humidity cabinet at 100 F and in circulating air at 650 F	CE1	57,900	
	CE2	57,060	
	CE3	57,100	
	CE4	57,000	
	CE7	57,500	
	CE8	58,000	

TABLE VIII - Maximum Stress Levels

Test Material: AM 350 M

ENVIRONMENT	SPECIMEN NUMBER	MAX. STRESS psi	K_t
	DA1	56,800	
	DA2	57,400	
	DA3	57,500	
Continuous exposure in circulating air at 650 F	DA4	57,100	
	DA5	159,200	1.745
	DA6	157,900	1.745
	DA7	54,500	
Coated with synthetic sea salt and then continuous exposure in circulating air at 650 F	DB1	54,500	
	DB2	53,600	
	DB3	56,600	
	DB4	57,100	
	DB5	151,500	1.762
	DB6	146,700	1.77
	DB7	54,500	
	DC1	48,800	
	DC2	49,900	
Coat with brazing alloy and then continuous exposure in circulating air at 650 F	DC3	49,700	
	DC4	50,400	
	DC5	137,200	1.8
	DC6	129,600	1.814
	DC7	49,800	
	DD1	50,400	
Coated with brazing alloy plus synthetic sea salt and then continuous exposure in circulating air at 650 F	DD2	49,600	
	DD3	50,800	
	DD4	50,800	
	DD5	130,200	1.814
	DD6	136,200	1.80
	DD7	50,800	
Coated with synthetic sea salt, then alternating 14 day exposure in humidity cabinet at 100 F and in circulating air at 650 F	DE1	55,600	
	DE2	55,600	
	DE3	55,600	
	DE4	54,900	

TABLE IX - Maximum Stress Levels

Test Material: Inconel 718

ENVIRONMENT	SPECIMEN NUMBER	MAX. STRESS psi	K_t
Continuous exposure in circulating air at 650 F	EA1	39,600	
	EA2	39,000	
	EA3	40,000	
	EA4	36,600	
	EA5	105,500	1.885
	EA6	105,500	1.885
	EA7	39,400	
Coated with synthetic sea salt and then continuous exposure in circulating air at 650 F	EB1	37,400	
	EB2	36,800	
	EB3	38,800	
	EB4	39,400	
	EB5	99,200	1.895
	EB6	107,600	1.875
	EB7	39,400	
Coat with brazing alloy and then continuous exposure in circulating air at 650 F	EC1	33,800	
	EC2	33,300	
	EC3	35,400	
	EC4	34,800	
	EC5	101,900	1.895
	EC6	98,400	1.915
	EC7	35,400	
Coated with brazing alloy plus synthetic sea salt and then continuous exposure in circulating air at 650 F	ED1	35,400	
	ED2	34,900	
	ED3	35,200	
	ED4	34,900	
	ED5	94,400	1.92
	ED6	94,800	1.92
	ED7	35,400	
Coated with synthetic sea salt, then alternating 14 day exposure in humidity cabinet at 100 F and in circulating air at 650 F	EE1	39,400	
	EE2	37,900	
	EE3	37,800	
	EE4	38,600	
	EE7	39,300	

TABLE X - Maximum Stress Levels

Test Material: Rene' 41

ENVIRONMENT	SPECIMEN NUMBER	MAX. STRESS psi	K_t
Continuous exposure in circulating air at 650 F	FA1	53,100	
	FA2	53,600	
	FA3	54,100	
	FA4	53,000	
	FA5	147,600	1.780
	FA6	146,600	1.780
	FA7	53,100	
Coated with synthetic sea salt and then continuous exposure in circulating air at 650 F	FB1	53,900	
	FB2	52,600	
	FB3	52,900	
	FB4	53,600	
	FB5	145,700	1.780
	FB6	150,600	1.772
	FB7	53,100	
Coat with brazing alloy and then continuous exposure in circulating air at 650 F	FC1	47,800	
	FC2	47,500	
	FC3	48,400	
	FC4	48,000	
	FC5	131,800	1.820
	FC6	128,400	1.83
	FC7	48,800	
Coated with brazing alloy plus synthetic sea salt and then continuous exposure in circulating air at 650 F	FD1	48,800	
	FD2	48,900	
	FD3	47,600	
	FD4	48,800	
	FD5	130,400	1.820
	FD6	133,500	1.830
	FD7	48,800	
Coated with synthetic sea salt, then alternating 14 day exposure in humidity cabinet at 100 F and in circulating air at 650 F	FE1	54,500	
	FE2	53,700	
	FE3	55,900	
	FE4	53,300	
	FE7	52,000	
	FE8	54,200	

Table XI . Summary of Titanium 6Al-4V Alloy Specimen Failures to 15,000 Hours Exposure and Unnotched and Notched Tensile Properties of these specimens

SPECIMEN SURFACE TREATMENT AND EXPOSURE ENVIRONMENT	SPEC NO.	EXPOSURE TEST TIME (hours)	FAILURE	UNNOTCHED PROPERTIES: UNSTRESSED AREA Ftu	UNSTRESSED AREA Fty	UNSTRESSED AREA %El.	STRESSED AREA Ftu	STRESSED AREA Fty	STRESSED AREA %El.	NOTCHED PROPERTIES: UN-STRESSED AREA Ftu	STRESSED AREA Ftu
No surface coating. Continuous exposure in circulating air at 650°F	AA1	10,000	None	162.3	147.7	16.0	149.0	131.5	14.0	170.0	173.0(2)
	AA2	15,000	None	162.0	150.0	14.2	162.0	148.0	14.2	173.0	181.0
Coated with synthetic sea salt. Continuous exposure in circulating air at 650°F	AB1	10,000	None	162.4	145.9	18.0	162.0	146.6	18.0	170.0	172.0(2)
	AB2	15,000	None	160.0	147.0	16.5	162.0	146.0	14.2	179.0	181.0
Coated with braze alloy. Continuous exposure in circulating air at 650°F	AC2	9,740	Broke	137.3	123.3	(1)	150.0	131.2	(1)	142.0	147.0(2)
	AC3	7,124	Broke	140.6	123.4	4.4	129.9	126.8	(1)(2)	153.0	149.0
	AC5	9,572	Bent	135.0	115.0	7.8	138.4	123.0	8.0	160.0	156.0
	AC6	5,516	Broke	134.0	112.0	7.2	135.0	118.0	8.0	146.0	148.0
Coated with braze alloy plus synthetic sea salt. Continuous exposure in circulating air at 650°F	AD2	15,000	Bent	154.0	133.5	10.2	156.0	138.0	11.0	164.0	165.0
	AD3	7,124	Broke	141.0	119.0	6.2	139.0	116.8	8.6	146.0	154.0
	AD5	15,000	Broke	148.0	126.0	9.5	155.0	135.0	11.0	164.0	165.0
Coated with synthetic sea salt. Alternating 14 day exposure in circulating air at 650°F and in 100°F humidity cabinet	AE1	10,000	None	161.0	147.0	14.4	161.0	132.0	15.4	183.0	174.0
	AE2	15,000	None	163.0	148.0	16.5	163.0	153.0	14.2	180.0	182.0
No surface coating and no exposure	AO,AP	Miniature Spec		160.5	150.8	(3)	Braze Coated Std Spec			176.0	(2)
	A	Standard Spec		160.9	151.2	11.0	148.0	125.0	14.9	183.6(4)	-

NOTES:
(1) Tensile specimens failed through grip hold
(2) 0.250 inch wide miniature tensile specimens
(3) Not determined
(4) TT-11013, Root Radius = 0.002 inch; K_t = 6 (edge "V" notch)

All stresses in KSI

Table XII. Summary of Titanium 8Al-1Mo-1V Alloy Specimen Failures to 15,000 Hours Exposure and Unnotched and Notched Tensile Properties of these specimens

SPECIMEN SURFACE TREATMENT AND EXPOSURE ENVIRONMENT	SPEC NO.	EXPOSURE TEST TIME (hours)	FAILURE	UNNOTCHED PROPERTIES						NOTCHED PROPERTIES	
				UNSTRESSED AREA			STRESSED AREA			UN-STRESSED AREA	STRESSED AREA
				Ftu	Fty	%El.	Ftu	Fty	%El.	Ftu	Ftu
No surface coating. Continuous exposure in circulating air at 650°F	BA1	10,000	None	143.0	129.0	19.2	148.2	136.0	17.6	148.0	151.0
	BA2	15,000	None	146.0	134.0	18.0	146.0	133.5	19.7	146.0	152.0
Coated with synthetic sea salt. Continuous exposure in circulating air at 650°F	BB1	3,980	Broke	139.0	129.0	15.2	141.0	129.0	15.4	149.0	149.0
	BB2	2,640	Broke	138.0	(1)	15.2	135.0	131.0	15.4	(5)	153.0
Coated with braze alloy. Continuous exposure in circulating air at 650°F	BC1	10,796	Broke	112.0	102.0	4.8	120.0	107.0	14.4	142.0	137.0
	BC2	9,308	Bent	119.0	109.0	8.8	129.0	119.4	8.0	138.0	143.0
	BC3	12,572	Broke								
	BC6	8,876	Broke	144.0	128.0	14.6	(2)	(2)	(2)	153.0	154.0
Coated with braze alloy plus synthetic sea salt. Continuous exposure in circulating air at 650°F	BD2	15,000	Bent	123.0	(3)	2.3	55.0	(3)	0.0	146.0	125.5(6)
	BD3	9,644	Broke	117.0	110.0	8.6	121.0	113.0	8.8	135.0	153.0
Caoted with synthetic sea salt. Alternating 14 day exposure in circulating air at 650°F and in 100°F humidity cabinet	BE1	10,000	None	150.0	138.0	18.8	143.0	132.0	20.0	149.0	154.0
	BE2	15,000	None	147.0	135.0	18.1	139.0	131.0	19.7	155.0	156.0
No surface coating and no exposure.	BO BP	Miniature Spec		147.0	134.0	17.8	Braze Coated Std Spec			154.0	-
	B	Standard Spec		153.0	143.4	14.6	140.0	133.0	13.6	159.7(4)	-

NOTES:
(1) Extensometer slipped.
(2) Broke through grip hole.
(3) Not determined.
(4) TT-11013, Root Radius = 0.002 inch; K_t = 6 (edge "V" notch)
(5) Material cracked, specimen not tested
(6) Did not break at notch
All stresses in KSI

Table XIII . Summary of PH15-7Mo Steel Specimen Failures to 15,000 Hours Exposure and Unnotched and Notched Tensile Properties of these specimens

SPECIMEN SURFACE TREATMENT AND EXPOSURE ENVIRONMENT	SPEC NO.	EXPOSURE TEST TIME (hours)	FAILURE	UNNOTCHED PROPERTIES: UNSTRESSED AREA Ftu	UNSTRESSED AREA Fty	UNSTRESSED AREA %El.	STRESSED AREA Ftu	STRESSED AREA Fty	STRESSED AREA %El.	NOTCHED PROPERTIES: UN-STRESSED AREA Ftu	STRESSED AREA Ftu
No surface coating. Continuous exposure in circulating air at 650°F	CA1	10,000	None	234.0	223.0	7.0	230.0	219.0	6.4	206.0	203.0
	CA2	15,000	None	225.0	216.0	6.3	223.0	216.0	4.7	250.0	241.0
Coated with synthetic sea salt. Continuous exposure in circulating air at 650°F	CB1	10,000	None	224.0	215.0	6.4	224.0	216.0	6.4	211.0	219.0
	CB2	15,000	None	227.0	220.0	5.5	228.0	220.0	6.3	249.0	254.0
Coated with braze alloy. Continuous exposure in circulating air at 650°F	CC1	10,000	None	224.0	213.0	6.4	223.0	214.0	7.4	202.0	199.0
	CC2	15,000	None	226.0	216.0	7.1	224.0	217.0	6.3	235.0	239.0
Coated with braze alloy plus synthetic sea salt. Continuous exposure in circulating air at 650°F	CD1	10,000	None	240.0	232.0	3.4	248.0	238.0	6.4	223.0	231.0
	CD2	15,000	None	224.0	219.0	8.6	223.0	213.0	6.3	225.0	226.0
Coated with synthetic sea salt. Alternating 14 day exposure in circulating air at 650°F and in 100°F humidity cabinet.	CE1	10,000	None	224.0	217.0	6.4	229.0	221.0	7.0	220.0	229.0
	CE2	15,000	None	231.0	215.0	7.1	230.0	210.0	9.4	243.0	242.0
No surface coating and no exposure	CO,CP	Miniature Spec		186.0	178.0	9.2		-		202.0	-
	C	Standard Spec		203.6	194.8	5.8		-		193.1(1)	-

NOTES: (1) TT-11013, Root Radius = 0.002 inch; $K_t = 6$ (edge "V" notch)

All stresses in KSI

Table XIV . Summary of AM 350 Steel Specimen Failures to 15,000 Hours Exposure and Unnotched and Notched Tensile Properties of these specimens

SPECIMEN SURFACE TREATMENT AND EXPOSURE ENVIRONMENT	SPEC. NO.	EXPOSURE TEST TIME (hours)	FAILURE	UNNOTCHED PROPERTIES						NOTCHED PROPERTIES	
				UNSTRESSED AREA			STRESSED AREA			UN-STRESSED AREA	STRESSED AREA
				Ftu	Fty	%El.	Ftu	Fty	%El.	Ftu	Ftu
No surface coating. Continuous exposure in circulating air at 650°F	DA1	10,000	None	204.0	172.0	10.8	203.0	168.0	8.6	203.0	207.0
	DA2	15,000	None	208.0	179.0	13.4	209.0	180.0	13.4	223.0	217.0
Coated with synthetic sea salt. Continuous exposure in circulating air at 650°F	DB1	10,000	None	202.0	170.0	12.2	210.0	177.0	12.2	216.0	173.0
	DB2	15,000	None	209.0	179.0	13.4	209.0	181.0	13.4	223.0	228.0
	DB5	10,796	Broke	205.0	172.0	4.4	207.0	167.0	5.8	211.0	208.0
	DB6	15,000	Broke	206.0	178.0	8.6	210.0	185.0	8.6	204.0	230.0
Coated with braze alloy. Continuous exposure in circulating air at 650°F	DC1	10,000	None	225.0	193.0	12.2	228.0	190.0	12.2	180.0	202.0
	DC2	15,000	None	202.0	171.0	13.4	201.0	171.0	11.8	231.0	220.0
Coated with braze alloy plus synthetic sea salt. Continuous exposure in circulating air at 650°F	DD1	10,000	None	220.0	185.0	7.8	225.0	192.0	7.8	191.0	173.0
	DD2	15,000	None	206.0	174.5	7.9	202.0	172.0	15.8	212.0	218.0
Coated with synthetic sea salt. Alternating 14 day exposure in circulating air at 650°F and in 100°F humidity cabinet.	DE1	3,360	Broke	202.0	170.0	7.8	(1)	(1)	(1)	(3)	
	DE2	3,290	Broke	199.0	159.0	9.8	189.0	164.0	4.0	210.0	
	DE3	3,290	Broke	198.0	162.0	8.6	(1)	(1)	(1)	207.0	
	DE4	2,880	Broke	195.0	160.0	9.4	203.0	164.0	8.6	206.0	201.0
No surface coating and no exposure	DO,DP	Miniature Spec		197.0	163.0	12.2		-		204.0	-
	D	Standard Spec		202.0	167.0	12.9		-		219.4(2)	-

NOTES:
(1) Broke through grip hole
(2) TT-11013, Root Radius = 0.002 inch; K_t = 6 (edge "V" notch)
(3) Scrapped in machining

All stresses in KSI

Table XV . Summary of Inconel 718 Alloy Specimen Failures to 15,000 Hours Exposure and Unnotched and Notched Tensile Properties of these specimens.

TREATMENT AND EXPOSURE ENVIRONMENT	SPEC. NO.	EXPOSURE TEST TIME (hours)	FAILURE	UNNOTCHED PROPERTIES						NOTCHED PROP.	
				UNSTRESSED AREA			STRESSED AREA			UN-STRESSED AREA	STRESSED AREA
				F_{tu}	F_{ty}	%El.	F_{tu}	F_{ty}	%El.	F_{tu}	F_{tu}
No surface coating. Continuous exposure in circulating air at 650°F	EA1	10,000	None	185.0	139.0	25.0	191.0	140.0	24.0	178.0	181.0
	EA2	15,000	None	191.0	142.0	27.6	190.0	139.5	26.8	190.0	187.0
Coated with synthetic sea salt. Continuous exposure in circulating air at 650°F	EB1	10,000	None	176.0	130.0	25.0	187.0	139.0	25.0	181.0	186.0
	EB2	15,000	None	190.0	140.0	26.0	191.0	145.5	26.0	186.0	193.0
Coated with braze alloy. Continuous exposure in circulating air at 650°F	EC1	10,000	None	176.0	131.0	23.8	173.0	133.0	12.8	176.0	175.0
	EC2	15,000	None	187.0	137.0	24.2	187.0	137.0	24.2	183.0	187.0
Coated with braze alloy plus synthetic sea salt. Continuous exposure in circulating air at 650°F	ED1	10,000	None	187.0	139.0	22.0	192.0	139.0	22.0	176.0	181.0
	ED2	15,000	None	189.0	140.0	26.0	188.0	140.5	26.0	186.0	189.0
Coated with synthetic sea salt. Alternating 14 day exposure in circulating air at 650°F and in 100°F humidity cabinet	EE1	15,000	None	190.0	141.0	22.0	182.0	133.0	26.0	191.0	185.0
	EE2	10,000	None	189.0	139.0	25.0	192.0	143.0	25.0	186.0	184.0
No surface coating and no exposure	EO,EP	Miniature Spec		178.0	132.0	25.0		-		181.0	-
	E	Standard Spec		190.0	140.6	20.2		-		176.6(1)	-

NOTES: (1) TT-11013, Root Radius = 0.002 inch; K_t = 6 (edge "V" notch).

All stresses in KSI

Table XVI. Summary of Rene' 41 Alloy Specimen Failures to 15,000 Hours Exposure and Unnotched and Notched Tensile Properties of these specimens

SPECIMEN SURFACE TREATMENT AND EXPOSURE ENVIRONMENT	SPEC NO.	EXPOSURE TEST TIME (hours)	FAILURE	UNNOTCHED PROPERTIES: UNSTRESSED AREA Ftu	UNNOTCHED PROPERTIES: UNSTRESSED AREA Fty	UNNOTCHED PROPERTIES: UNSTRESSED AREA %El.	UNNOTCHED PROPERTIES: STRESSED AREA Ftu	UNNOTCHED PROPERTIES: STRESSED AREA Fty	UNNOTCHED PROPERTIES: STRESSED AREA %El.	NOTCHED PROP.: UN-STRESSED AREA Ftu	NOTCHED PROP.: STRESSED AREA Ftu
No surface coating. Continuous exposure in circulating air at 650°F	FA1	10,000	None	225.0	162.0	22.0	223.0	161.0	14.0	175.0	174.0
	FA2	15,000	None	207.0	145.0	22.0	201.0	147.0	18.1	177.0	180.0
Coated with synthetic sea salt. Continuous exposure in circulating air at 650°F	FB1	10,000	None	226.0	164.0	16.0	228.0	165.0	20.3	169.0	173.0
	FB2	15,000	None	205.0	144.5	18.1	206.0	134.0	23.6	176.0	188.0
Coated with braze alloy. Continuous exposure in circulating air at 650°F	FC1	10,000	None	192.0	146.0	14.4	198.0	148.0	21.2	177.0	170.0
	FC2	15,000	None	193.0	144.0	14.2	203.0	147.0	22.0	181.0	180.0
Coated with braze alloy plus synthetic sea salt. Continuous exposure in circulating air at 650°F	FD1	10,000	None	196.0	143.0	20.0	198.0	145.0	20.0	174.0	175.0
	FD2	15,000	None	193.0	140.0	19.7	200.0	150.0	16.3(1)	171.0	184.0
Coated with synthetic sea salt. Alternating 14 day exposure in circulating air at 650°F and in 100°F humidity cabinet	FE1	10,000	None	229.0	165.0	17.6	231.0	165.0	22.2	176.0	174.0
	FE2	15,000	None	207.0	147.5	23.6	206.0	148.0	22.0	183.0	178.0
No surface coating and no exposure	FO,FP	Miniature Spec		188.0	132.0	19.0		-		168.0	-
	F	Standard Spec		195.2	147.5	13.4		-		167.9(2)	-

NOTES: (1) Failure through gage mark; elongation approximate only.
(2) TT-11013, Root Radius = 0.002 inch; K_t = 6 (edge "V" notch)

All stresses in KSI

Table XVII. Appearance of Unfractured Specimens After 2,800 Hours Exposure

SPECIMEN SURFACE TREATMENT AND EXPOSURE ENVIRONMENT	GENERAL APPEARANCE OF EXPOSED TEST SPECIMENS
No surface coating. Continuous exposure in circulating air at 650°F	No evidence of corrosion, slight discoloration of all specimens, particularly those fitted on the lowest frame level (titanium and ferrous alloys).
Coated with synthetic sea salt. Continuous exposure in circulating air at 650°F.	Spotty salt coating, causing rust like spots associated with local salt deposits. All specimens discolored.
Coated with braze alloy. Continuous exposure in circulating air at 650°F.	No change in appearance.
Coated with braze alloy plus synthetic sea salt. Continuous exposure in circulating air at 650°F.	Original salt spotting associated with heavy rust spotting in ferrous alloys. All specimens somewhat discolored.
Coated with synthetic sea salt. Alternating 14 day exposure in circulating air at 650°F and in 100°F humidity cabinet.	Iron and nickel alloys have a roughened surface and iron alloys show considerable rusting. Titanium alloys have a smooth surface, but show blue-gray discoloration.

Table XVIII. Appearance of Unfractured Specimens After 4,700 Hours Exposure.

SPECIMEN SURFACE TREATMENT AND EXPOSURE ENVIRONMENT	GENERAL APPEARANCE OF EXPOSED TEST SPECIMENS
No surface coating. Continuous exposure in circulating air at 650°F.	Titanium and ferrous alloy show slight blueing. All specimens are smooth.
Coated with synthetic sea salt. Continuous exposure in circulating air at 650°F.	The ferrous alloy specimens show a surface color darkened from gold to brown. Unnotched ferrous alloy specimens have about 20% of the surface coated with rust spots, notched ferrous alloy specimens about 50%. The other specimens show a darkening of the surface and a few rust like spots. The salt coating appears to be spotty.
Coated with braze alloy. Continuous exposure in circulating air at 650°F.	The surface shows only a slight darkening, with no evidence of any corrosion products.
Coated with braze alloy plus synthetic sea salt. Continuous exposure in circulating air at 650°F.	The titanium alloy specimens have darkened considerably to a dark brown, titanium alloy specimens fitted to the bottom layer of the frame and all ferrous alloy specimens show about 50% of their surface covered with rust like spots.
Coated with synthetic sea salt. Alternating 14 day exposure in circulating air at 650°F and in 100°F humidity cabinet.	The ferrous alloy specimens and the Inconel 718 and Rene' 41 specimens have a rough surface and show considerable rusting. Titanium specimens are smooth, but show a blue gray discoloration.

Table XIX . Appearance of Unfractured Specimens After 8,900 Hours Exposure.

SPECIMEN SURFACE TREATMENT AND EXPOSURE ENVIRONMENT	GENERAL APPEARANCE OF EXPOSED TEST SPECIMENS
No surface coating. Continuous exposure in circulating air at 650°F.	The titanium alloys have a metallic blue coloration, the Inconel 718 and AM 350 specimens a blue coloration with some whitish spots. The PH15-7Mo and Rene' 41 specimens have a dark gray coloration. All specimens are smooth.
Coated with synthetic sea salt. Continuous exposure in circulating air at 650°F.	The salt coating appeared to be as laid down originally. The titanium alloys have a blue coloration with blue-gray discoloration spots covering about 30% of the surface. Ferrous alloys are smooth gray with about 20% of the surface covered with rust spots. Inconel 718 and Rene' 41 specimens have a smooth gray surface with no discoloration.
Coated with braze alloy. Continuous exposure in circulating air at 650°F.	The braze coating on all titanium alloy specimens is flaking off and has lost all adhesion. Below the braze coating the specimens have turned green and show a coarse crystalline surface. PH15-7Mo specimens have turned to a spotty gold color, AM 350 specimens to a purple-gold color. The Inconel 718 and Rene' 41 alloy specimens have turned dark gray. Only the titanium alloy specimens show any attack to the braze coating.
Coated with braze alloy plus synthetic sea salt. Continuous exposure in circulating air at 650°F.	The braze coating on all titanium alloy specimens is flaking off and has lost all adhesion. Below the braze coating the specimens have turned green and show a coarse crystalline surface. The salt coat on the ferrous and nickel-base alloys appears to be largely undisturbed. No change in appearance is evidenced by the nickel-base alloy specimens, but the braze coating on the ferrous alloy specimens are covered over about 20% of the surface with brown spots.
Coated with synthetic sea salt. Alternating 14 day exposure in circulating air at 650°F and in 100°F humidity cabinet.	The Rene' 41 specimens are smooth and show a gray discoloration. The Inconel 718 specimens are also smooth, but shown a brown discoloration. The ferrous alloy specimens have a dark brown coating and a rusted appearance. The titanium alloy specimens are blued, with a considerable amount of the surface covered with blue-gray spots.

Table XX Appearance of Unfractured Specimens After 15,000 Hours Exposure.

SPECIMEN SURFACE TREATMENT AND EXPOSURE ENVIRONMENT	GENERAL APPEARANCE OF EXPOSED TEST SPECIMENS
No surface coating. Continuous exposure in circulating air at 650°F.	All specimens had smooth surfaces. The titanium alloys were bright purple with all Ti 6Al-4V specimens and some of the Ti 8Al-1Mo-1V specimens having a mottled appearance. The AM 350 and Inconel 718 specimens were purple-gray with a brownish or yellowish discoloration on several specimens. The PH15-7Mo specimens were dark gray to light grayish-green. The Rene' 41 specimens were light yellow-green or light greenish-gray.
Coated with synthetic sea salt. Continuous exposure in circulating air at 650°F.	The salt coating appeared to be almost undisturbed on all specimens except on the PH15-7Mo and AM 350 notched specimens, the surfaces of which were badly attacked. The metallic specimen surfaces, where visible, were similar in appearance to those specimens which had been exposed without a coating.
Coated with braze alloy. Continuous exposure in circulating air at 650°F.	The braze coating on the titanium alloy specimens was a dark gray thin foil-like skin peeling off the specimen surfaces. The unnotched AM 350, Inconel 718 and Rene' 41 specimens had a bluish-gray color, with specimens of the latter two alloys showing a uniform shallow attack. The unnotched PH15-7Mo specimen surfaces had a splotched yellowish or yellowish-green cast. The notched PH15-7Mo, Inconel 718 and Rene' 41 specimens had blue-gray surfaces showing a uniform attack. The notched AM 350 specimens had yellowish-green surfaces with small reddish spots.
Coated with braze alloy plus synthetic sea salt. Continuous exposure in circulating air at 650°F.	The braze coating on the titanium alloy specimens was a dark gray or blue-gray skin peeling off the specimen surfaces; the notched Ti 8Al-1Mo-1V alloy specimen surfaces were badly attacked. The PH15-7Mo and AM 350 specimens were brownish-gray, with rust areas on the edges of the notched specimens. Specimens CD4 and DD4, both added at 10,000 hours test time, had dark purple pitted surfaces with AM 350 specimen DD4 highly attacked. Inconel 718 and Rene' 41 specimen surfaces were light gray to dark gray in color.
Coated with synthetic sea salt. Alternating 14 day exposure in circulating air at 650°F and in 100°F humidity cabinet.	The titanium alloy specimens all had whitish powdery deposits over a bluish substrate. PH15-7Mo, Inconel 718 and Rene' 41 specimens all showed surface pitting with whitish powdery corrosion products overlaid on a dark discolored corrosion substrate. No AM 350 specimens of this group remained in test.

TABLE XXI

ANALYSIS OF SALT COATING FROM 8-1-1 TITANIUM ALLOY, EXPOSED TO 650 F FOR 15,000 HOURS

LINE	INTENSITY	SPACING	NaCl	NaOH	MgO
1	w	3.255	3.258		
2	vvs	2.805	2.82	2.85	
3	vvw	2.096	-		2.106
4	vs	1.993	1.994	2.03	
5	vvw	1.693	-	1.70	
6	s	1.626	1.628		
7	f	1.48	-		
8	w	1.409	1.410		
9	f	1.29	-		
10	f	1.27	-	1.27	
11	m	1.260	1.261		
12	diff,w	1.151	1.1515		
13	w	0.997	0.9969		
14	w	0.953	0.9533		
15	dblt	0.940	0.9401		
16	dblt	0.891	0.8917		
17	dblt	0.849	0.8503		
18	dblt	0.783	-		
19	dblt	0.781	-		

TABLE - XXII

MATERIAL PROPERTIES

Temperature = 650°F

Material	E	G	ν	α in/in/°F	$\frac{E}{12(1-\nu^2)}$
6-4 Tit. FTU = 160	14.1×10^6	5.4×10^6**	.30*	$5. \times 10^{-6}$	1.2912×10^6
8-1-1 Tit. FTU = 140	15.5×10^6	5.96×10^6**	.30*	5.4×10^{-6}	1.419×10^6
PH15-7Mo FTU = 200	25.9×10^6	10.1×10^6	.308	6.15×10^{-6}	2.385×10^6
AM350 FTU = 200	25.6×10^6	9.9×10^6	.318	6.9×10^{-6}	2.373×10^6
INCONEL 718 FTU = 190	27.7×10^6	10.2×10^6	.303	7.9×10^{-6}	2.541×10^6
RENE' 41 FTU = 194	28.5×10^6	10.9×10^6	.318	7.05×10^{-6}	2.641×10^6

* Estimated

** Based on $G = \dfrac{E}{2(1+\nu)}$

TABLE XXIII

CALCULATIONS OF EFFECTIVE BEAM LENGTHS

Beam	δ (measured)	L^*	PL^{*2}/B	L	L_o
CA2	3.375"	9.74"	1.1887	9.7"	.00538"
DA3	3.625"	10.13"	1.2334	9.8"	.28962"
FA1	3.000"	10.16"	.957	9.73"	.38862"
BA2	4.500"	9.31"	1.9329	9.07"	.21093
AA2	3.152"	10.05"	1.0302	9.76"	.26093

$Lo_{AV} = .28752$

Thickness 't'	Titanium 6 Al-4 V	0.050 "
	Titanium 8Al-1V-1Mo	0.048" and 0.020"
	PH 15-7 Mo Steel	0.039"
	AM 350 M Steel	0.040"
	Inconel 718	0.042"
	Rene 41	0.050"

Depth of notch 0.010" ± 0.001" ; K_t 1.6 to 1.8

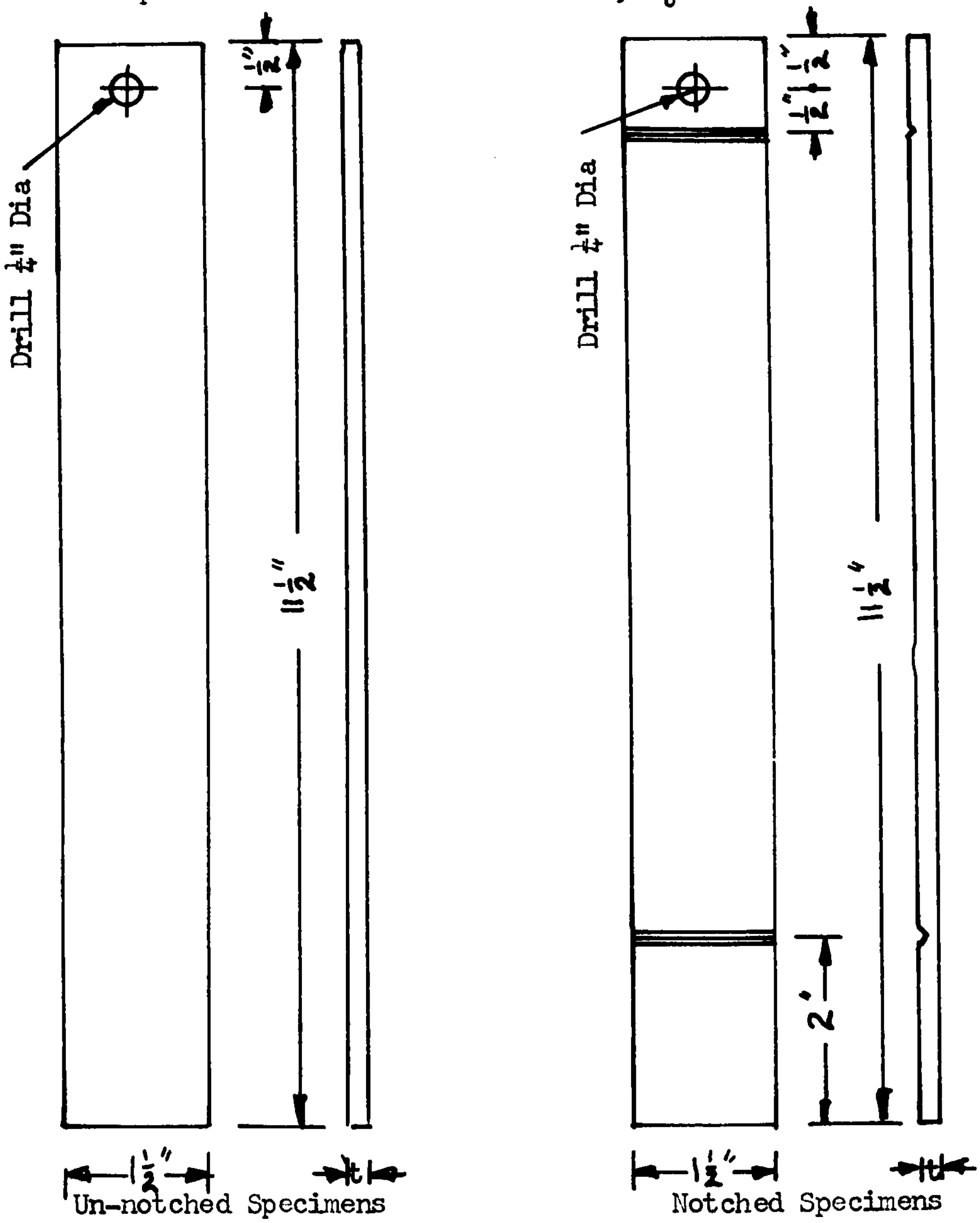


Figure 1; Dimensions of Exposure Specimens

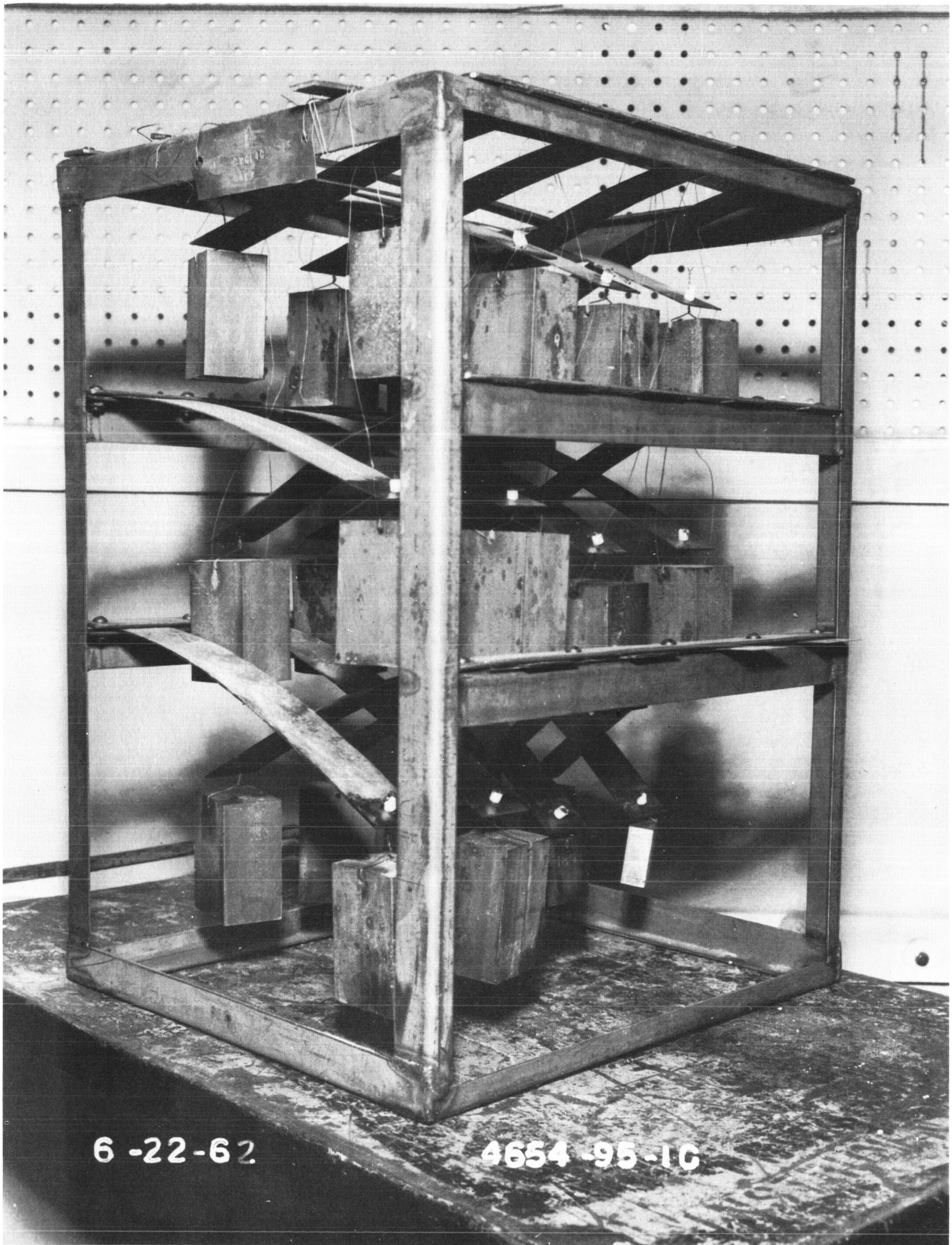


Figure 2 Exposure Specimens In Test Frame

Figure 3 Exposure Test Frames In Furnace

Each Specimen is identified by a four symbol code, as follows:

First symbol: Specimen Material	A	Titanium 6 Al-4 V alloy
	B	Titanium 8Al-1V-1Mo alloy
	C	PH 15-7 Mo Steel
	D	AM 350 M Steel
	E	Inconel 718
	F	Rene 41
Second symbol : Surface Treatment	A	None
	B	Salt Coating
	C	Braze Coating
	D	Salt plus Braze Coating
	E	Cyclic Exposure

Third symbol : Specimen Serial Number for each material and surface treatment

Fourth symbol : Specimen Position Code Letter as illustrated in the diagram below.

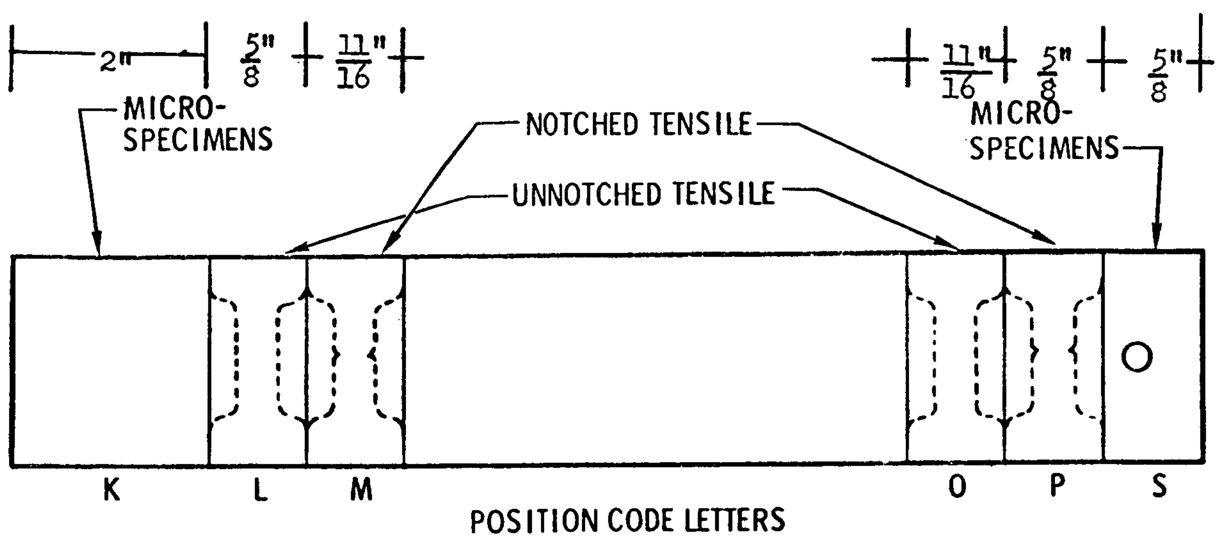
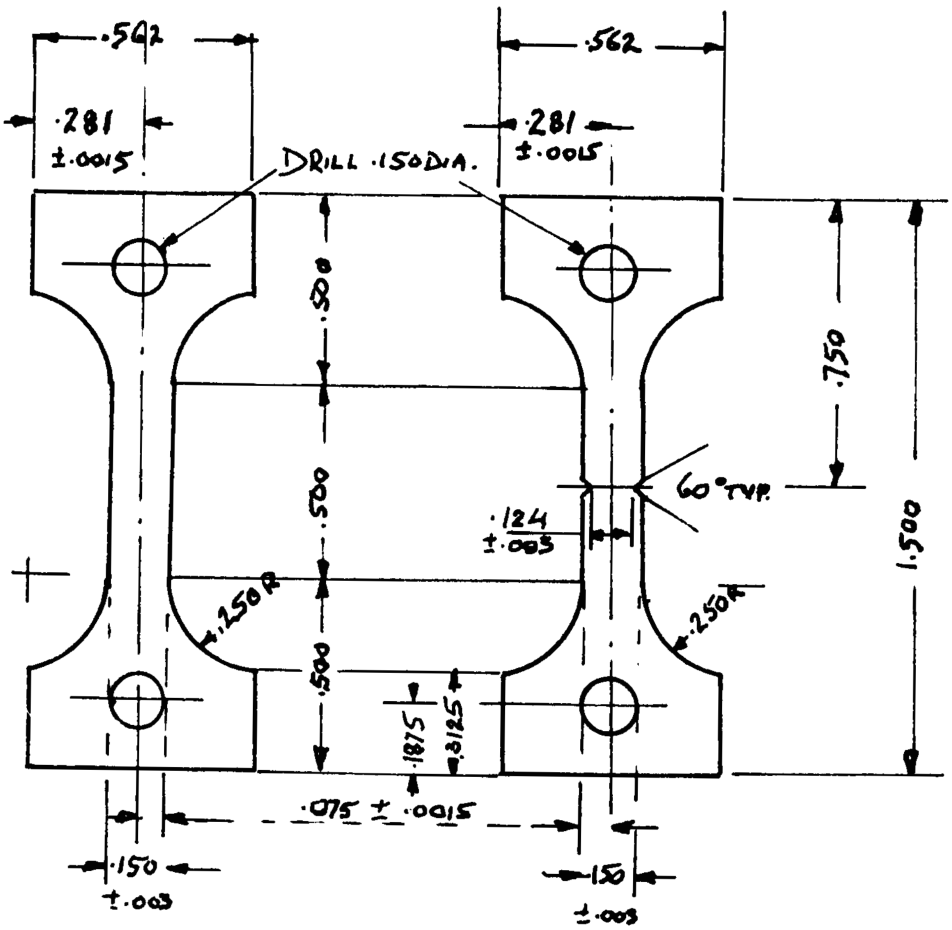


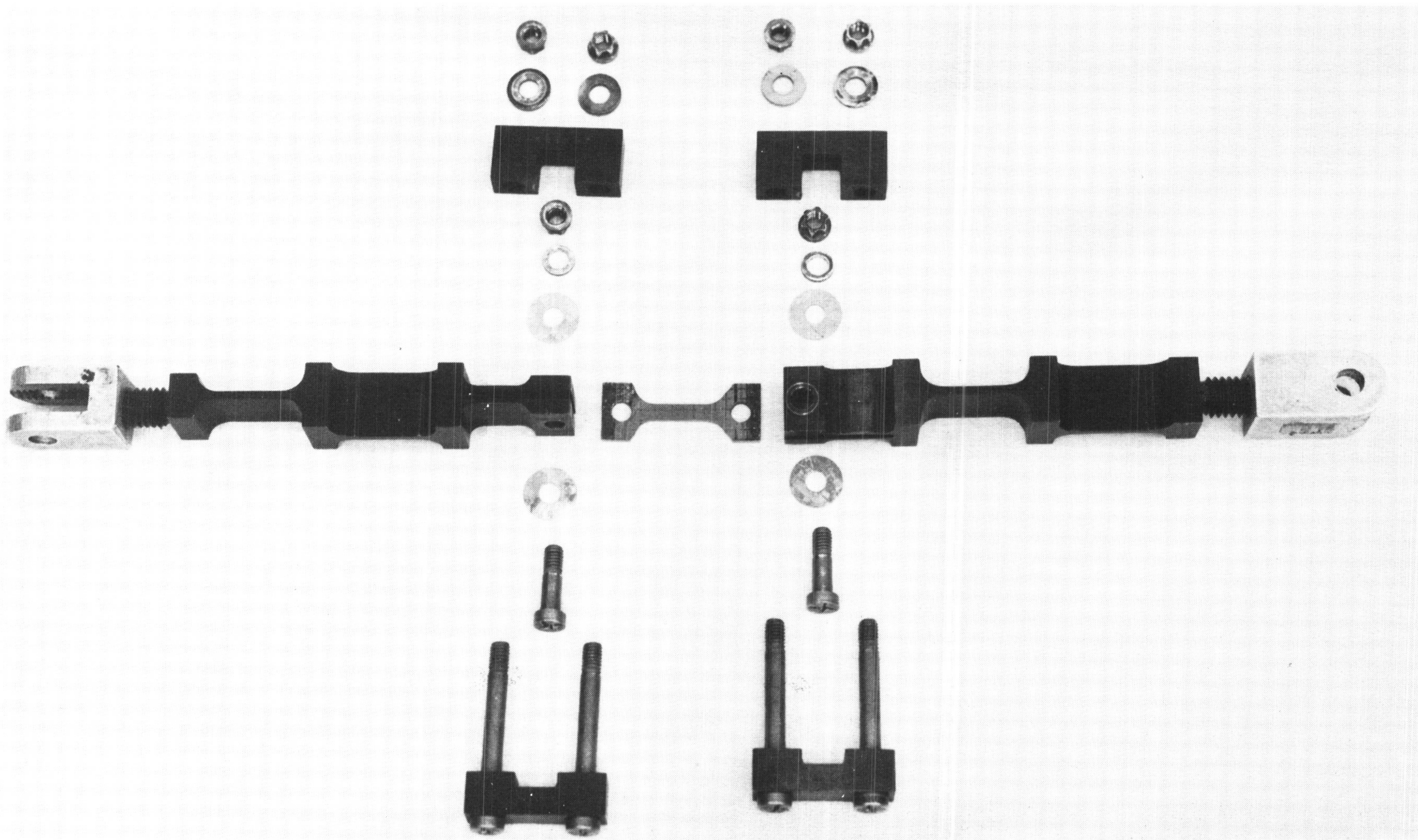
Figure 4; System of Marking and Cutting-up of Exposure Specimens and other Test Specimens.



NOTES: 1. Holes to be on centre line of notch root width ±.002.
2, Notch radius 0.002 maximum . $K_t = 6.0$
3. Notches to be made with light finishing cuts or light grinding and must have contour shown.
4. Tool Chatter or other Tool marks will be cause for reject. Do NOT buff.
5. Machine surface of notch
6. Notch and reduced section to be symmetrical about centre line ± .0015.

Figure 5 ; Notched and Un-notched Miniature Tensile Specimens.

Figure 6 Miniature Test Specimens Test Rig-
Components



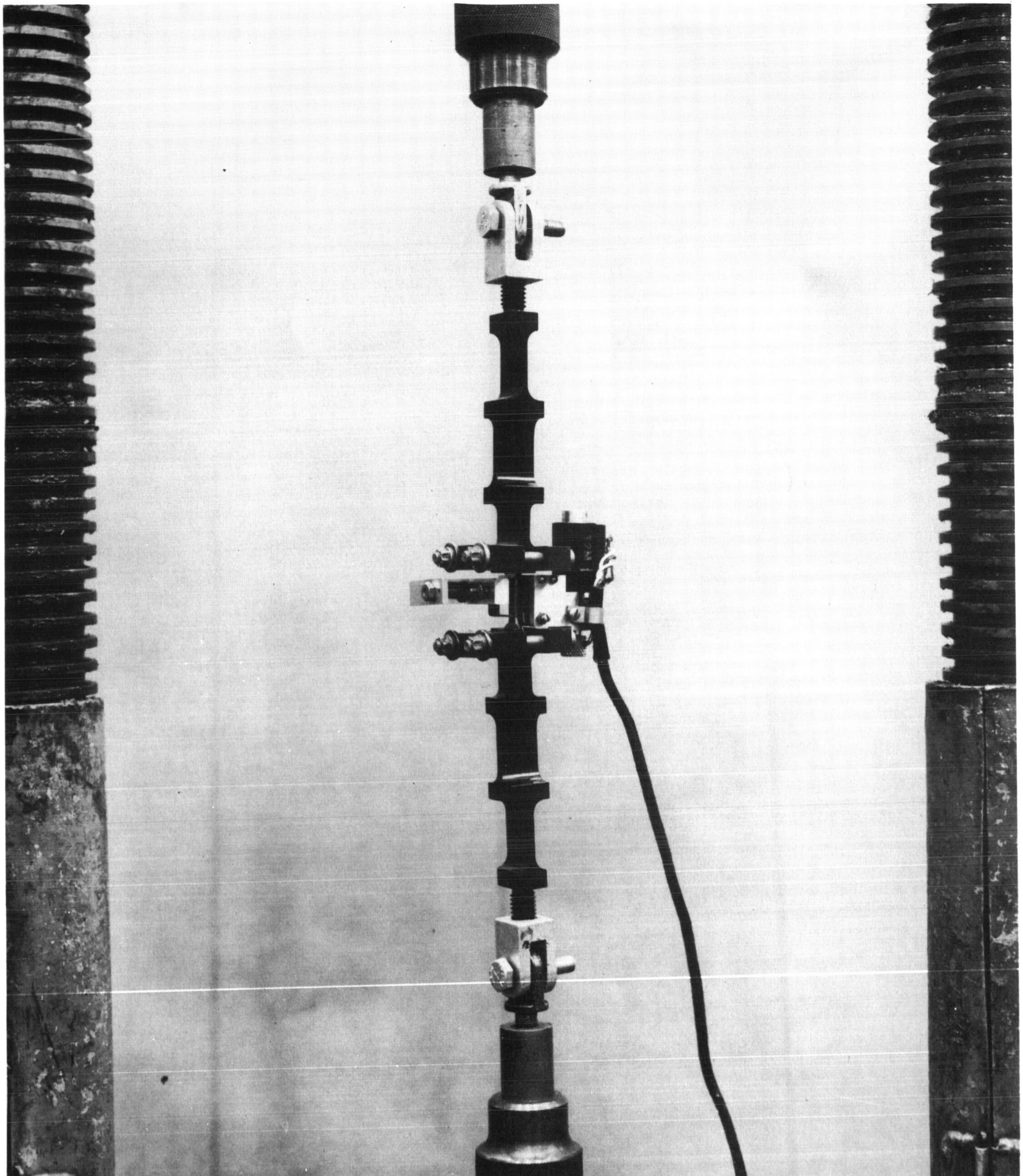
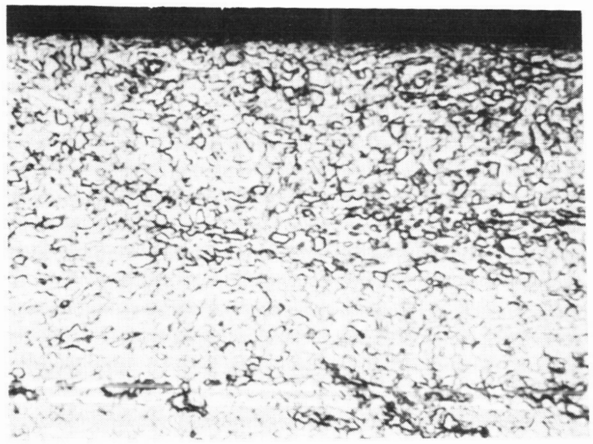
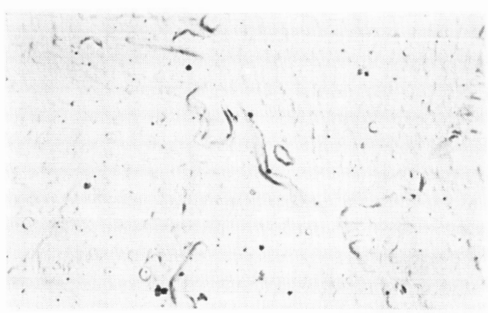


Figure 7 Miniature Test Specimens Test Rig-
Assembly with Extensometer



Etched x 500

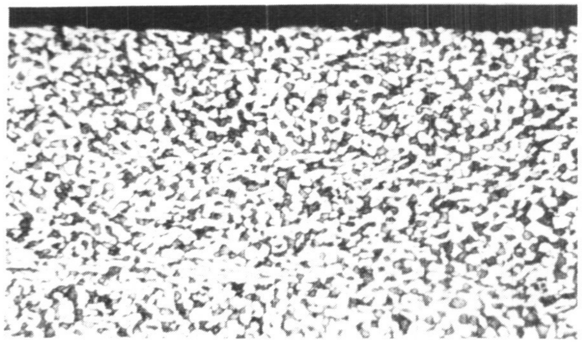
Two stage replica x 2500



Two stage replica x 15,000

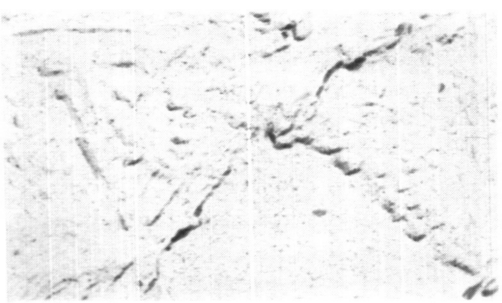
Figure 8.-Microstructure of Titanium 6Al-4V Alloy prior to exposure to test environment.

10,000 HOUR EXPOSURE
NO FAILURE



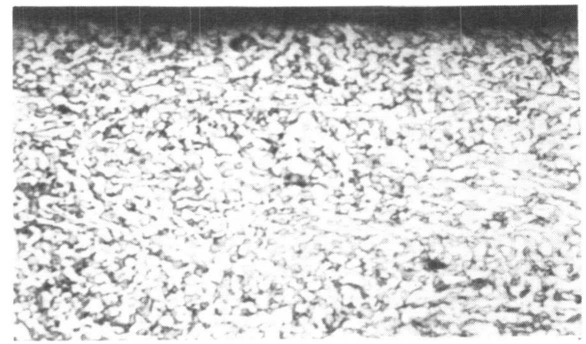
Etched x 500

Two stage replica x 2500

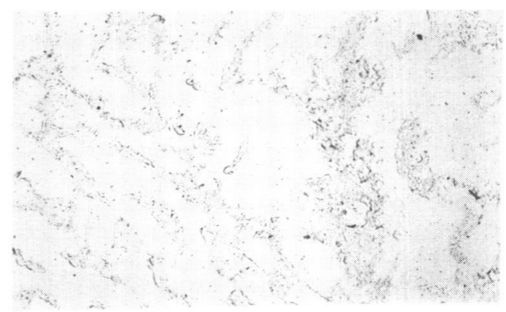


Two stage replica x 15,000

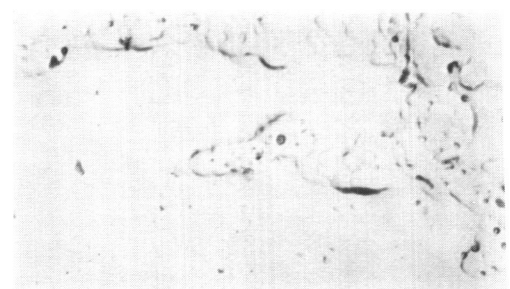
15,000 HOUR EXPOSURE
FAILED



Etched x 500

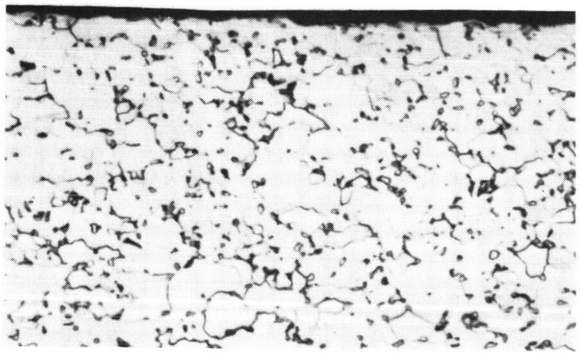


Two stage replica x 2500

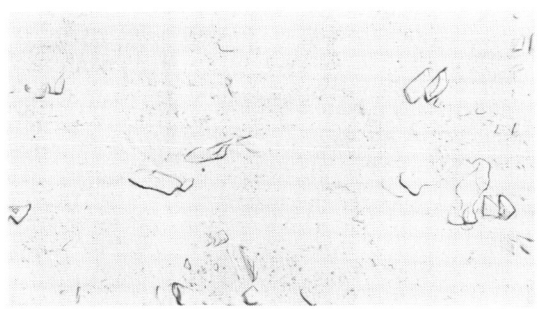


Two stage replica x 15,000

Figure 9 .- Microstructure of Salt Coated Titanium 6Al-4V Alloy after exposure in circulating air at 650°F. (Specimens AB1 and AB2)



Etched x 500

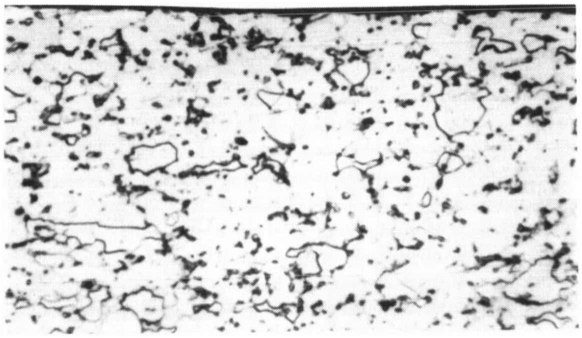


Two stage replica x 2500

Two stage replica x 15,000

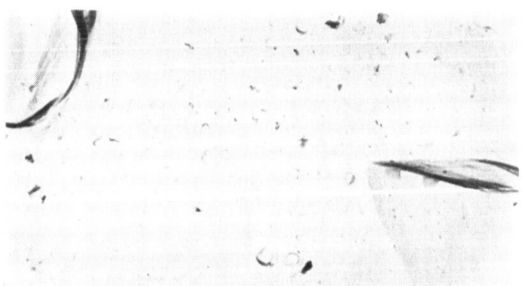
Figure 10 .-Microstructure of Titanium 8Al-1Mo-1V Alloy prior to exposure to test environment.

15,000 HOUR EXPOSURE
NO FAILURE



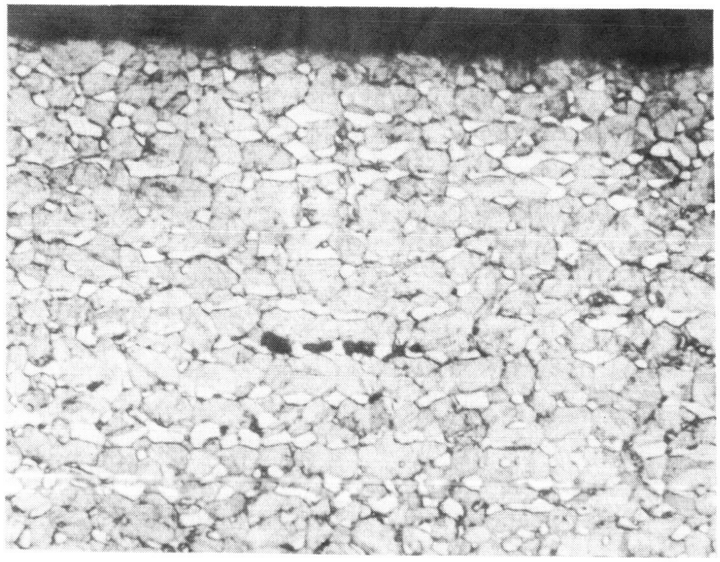
Etched x 500

Two stage replica x 2500

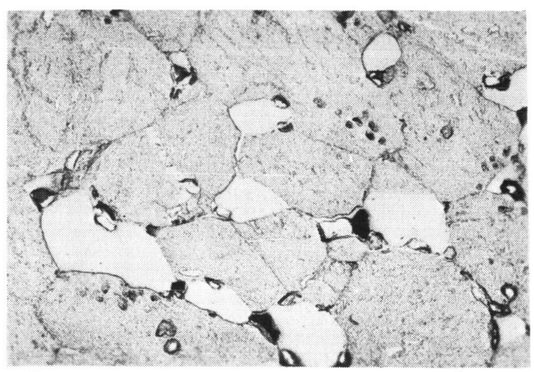


Two stage replica x 15,000

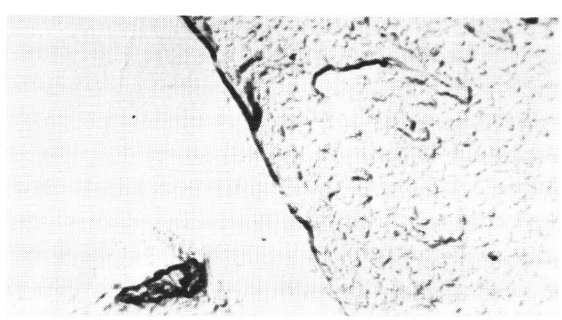
Figure 11.- Microstructure of Titanium 8Al-1Mo-1V Alloy after exposure in circulating air at 650°F. (Specimen BA2)



Etched x 500



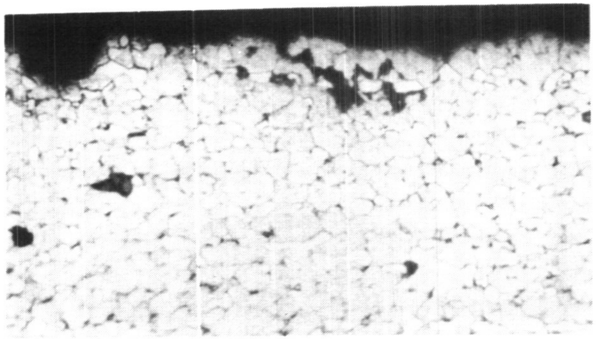
Two stage replica x 2500



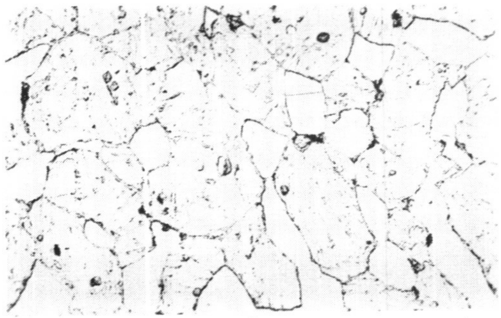
Two stage replica x 15,000

Figure 12.- Microstructure of PH15-7Mo Steel prior to exposure to test environment.

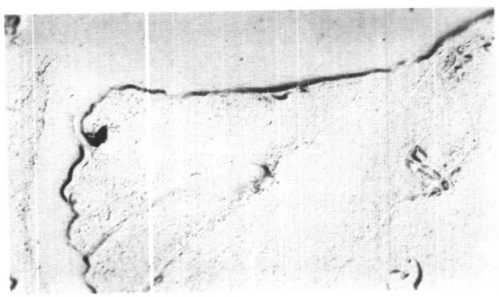
10,000 HOUR EXPOSURE
NO FAILURE



Etched x 500

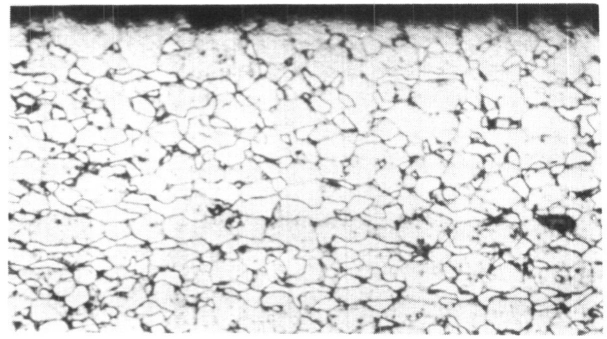


Two stage replica x 2500

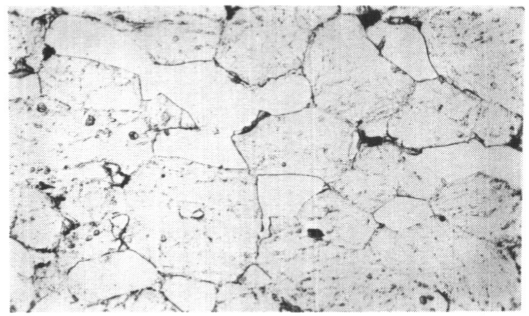


Two stage replica x 15,000

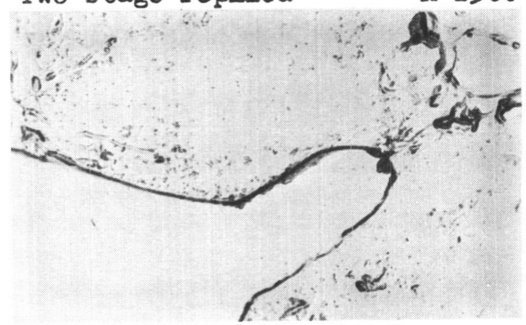
15,000 HOUR EXPOSURE
NO FAILURE



Etched x 500

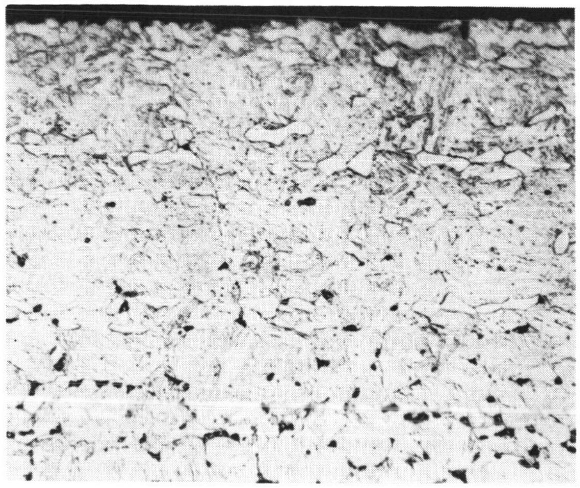


Two stage replica x 2500



Two stage replica x 15,000

Figure 13.- Microstructure of Salt Coated PH15-7Mo Steel after exposure in circulating air at 650°F. (Specimens CB1 and CB2)



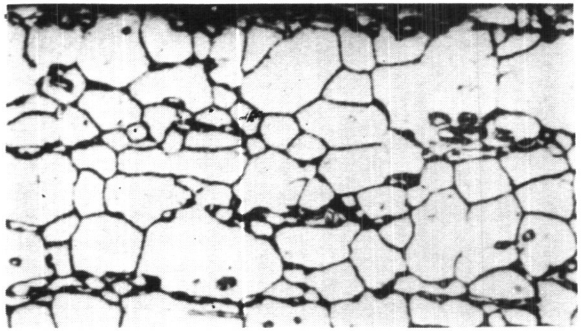
Etched x 500

Two stage replica x 2500

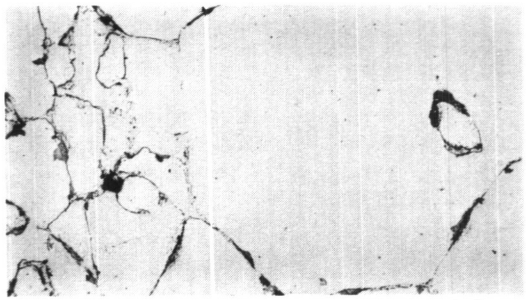
Two stage replica x 15,000

Figure 14.- Microstructure of AM 350 M Steel prior to exposure to test environment.

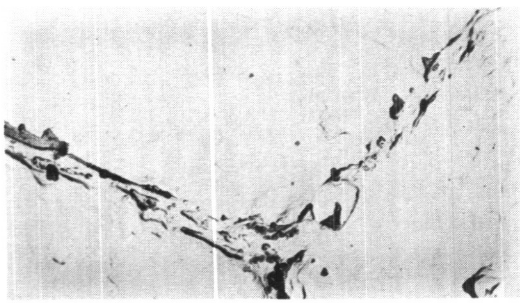
15,000 HOUR EXPOSURE
NO FAILURE



Etched x 500

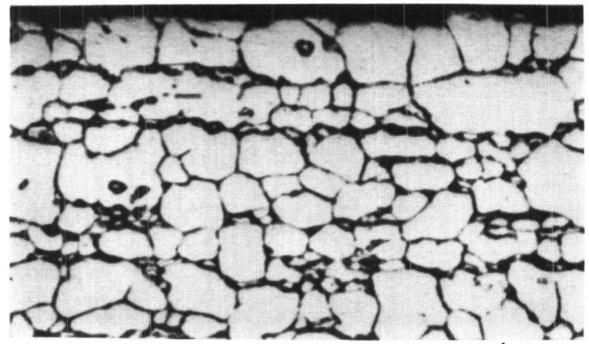


Two stage replica x 2500

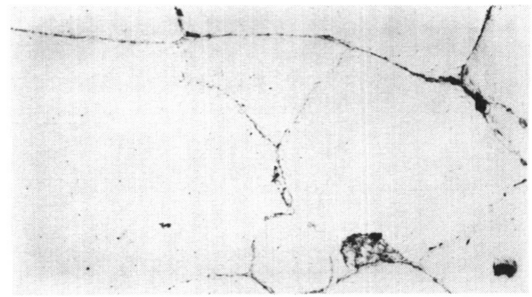


Two stage replica x 15,000

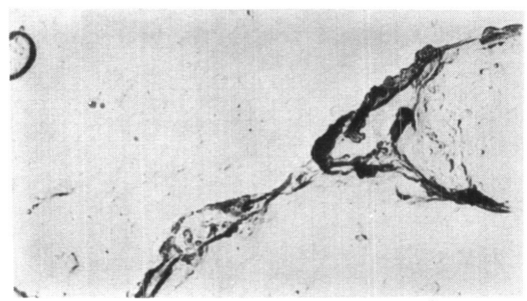
15,000 HOUR EXPOSURE
FAILED



Etched x 500

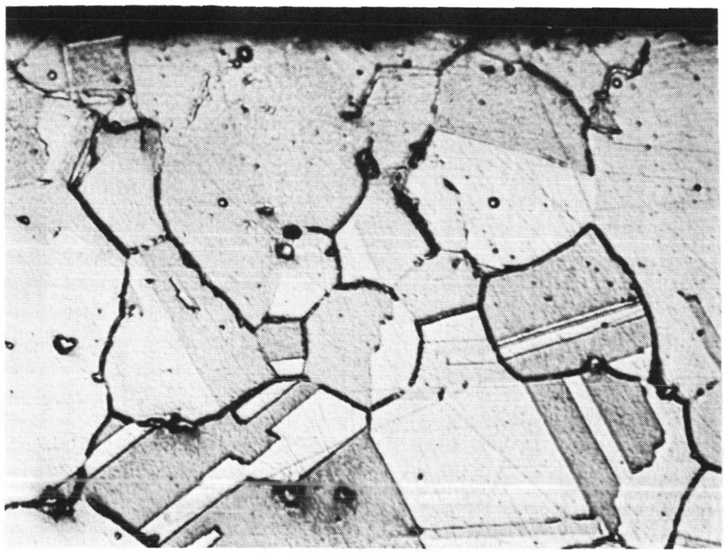


Two stage replica x 2500

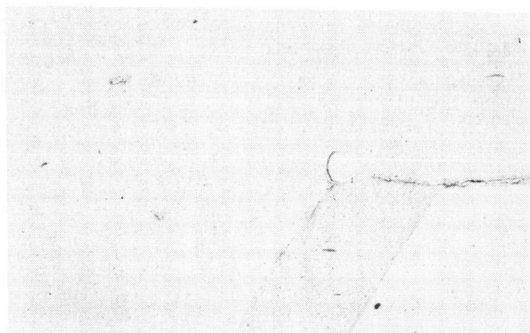


Two stage replica x 15,000

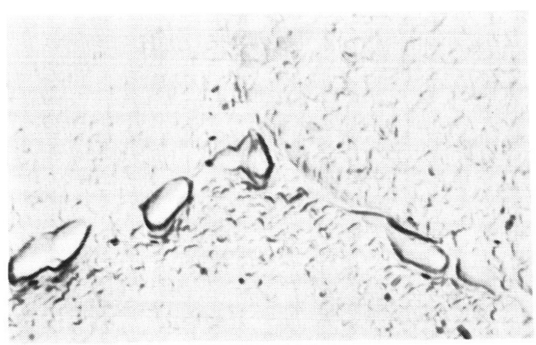
Figure 15.- Microstructure of Salt Coated AM 350 M Steel after exposure in circulating air at 650°F. (Specimens DB2 and DB6)



Etched x 500



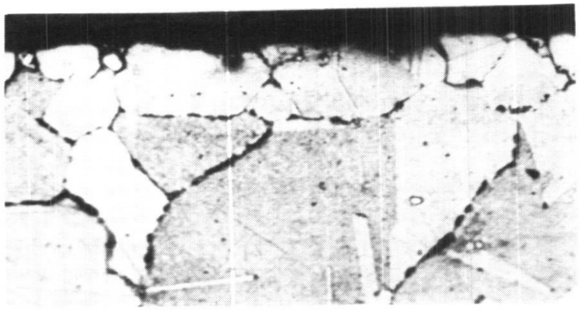
Two stage replica x 2500



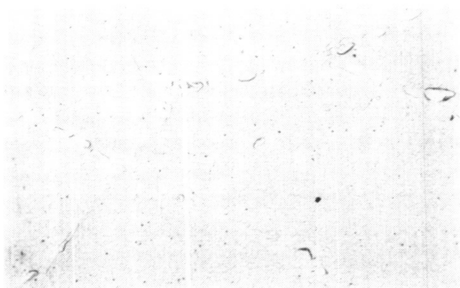
Two stage replica x 15,000

Figure 16 .- Microstructure of Inconel 718 Alloy prior to exposure to test environment.

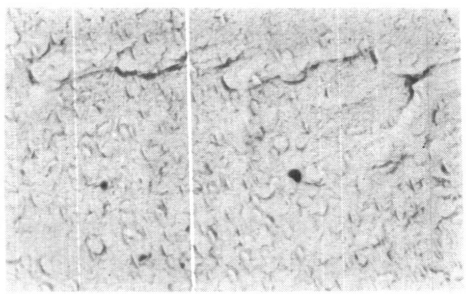
10,000 HOUR EXPOSURE
NO FAILURE



Etched x 500

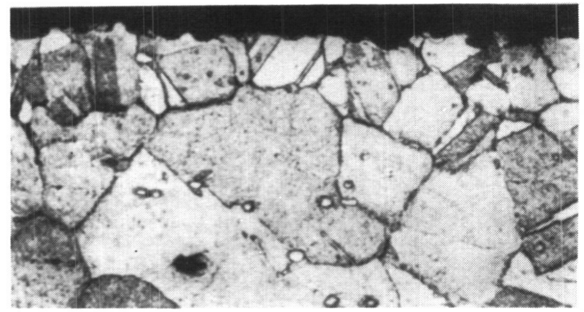


Two stage replica x 2500

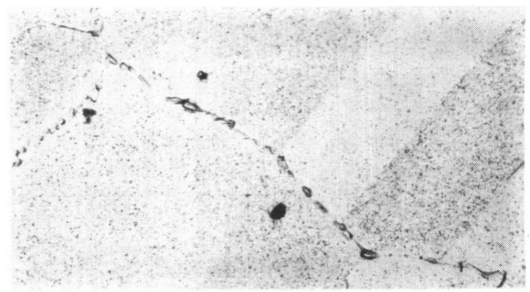


Two stage replica x 15,000

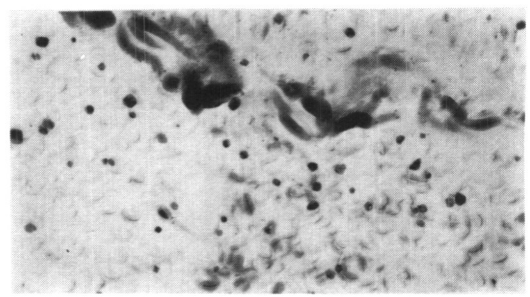
15,000 HOUR EXPOSURE
NO FAILURE



Etched x 500

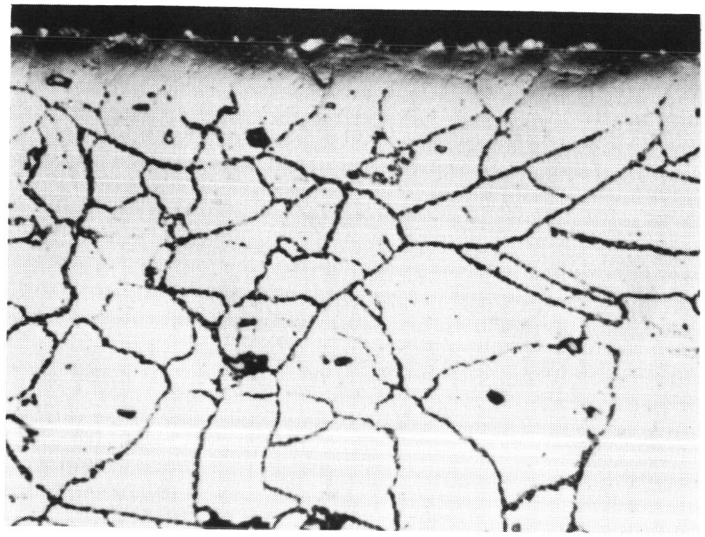


Two stage replica x 2500

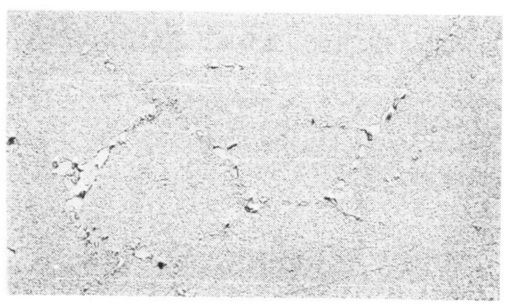


Two stage replica x 15,000

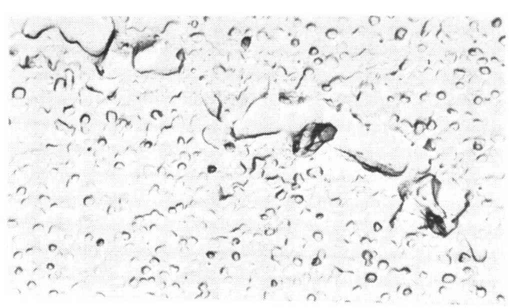
Figure 17.- Microstructure of Salt Coated Inconel 718 Alloy after exposure in circulating air at 650°F. (Specimens EB1 and EB2)



Etched x 500



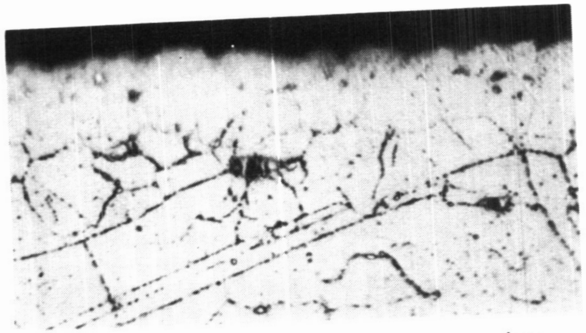
Two stage replica x 2500



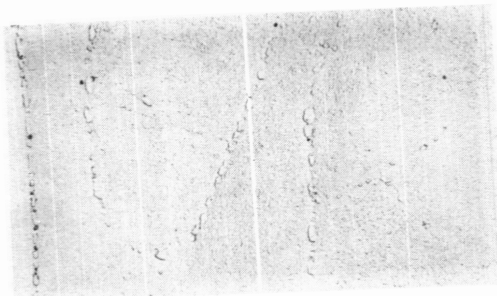
Two stage replica x 15,000

Figure 18.- Microstructure of Rene' 41 Alloy prior to exposure to test environment.

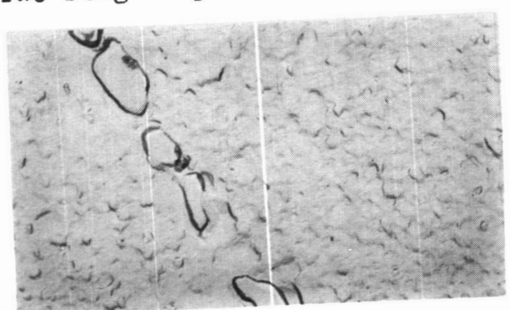
10,000 HOUR EXPOSURE
NO FAILURE



Etched x 500

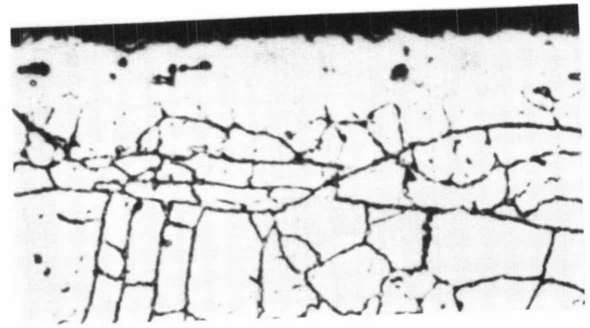


Two stage replica x 2500

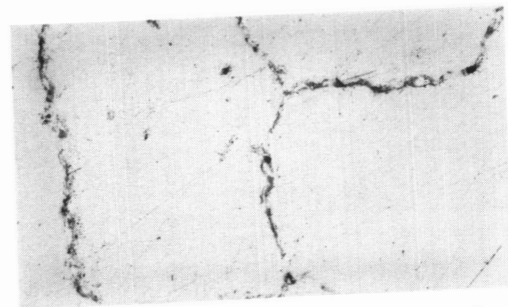


Two stage replica x 15,000

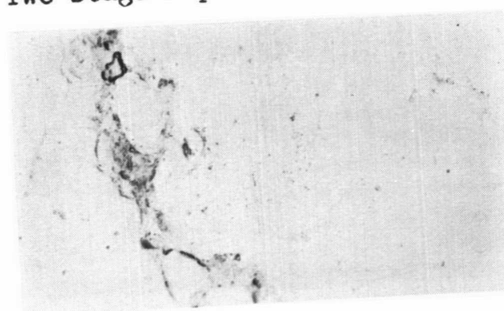
15,000 HOUR EXPOSURE
NO FAILURE



Etched x 500



Two stage replica x 2500



Two stage replica x 15,000

Figure 19.- Microstructure of Salt Coated Rene' 41 Alloy after exposure in circulating air at 650°F. (Specimens FB1 and FB2)

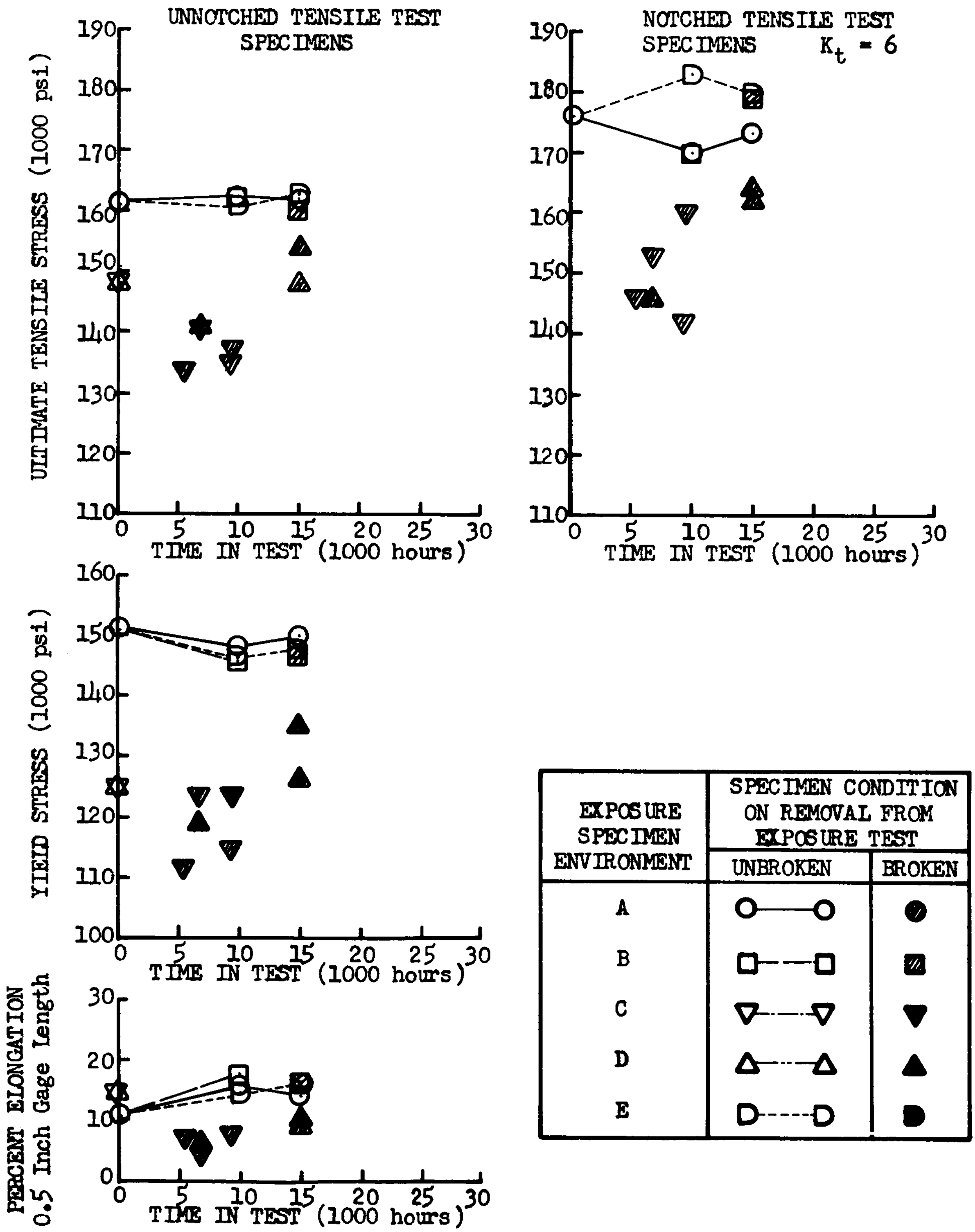


Figure 20.- Titanium 6Al-4V Alloy Unstressed Exposure Tensile Test Results.

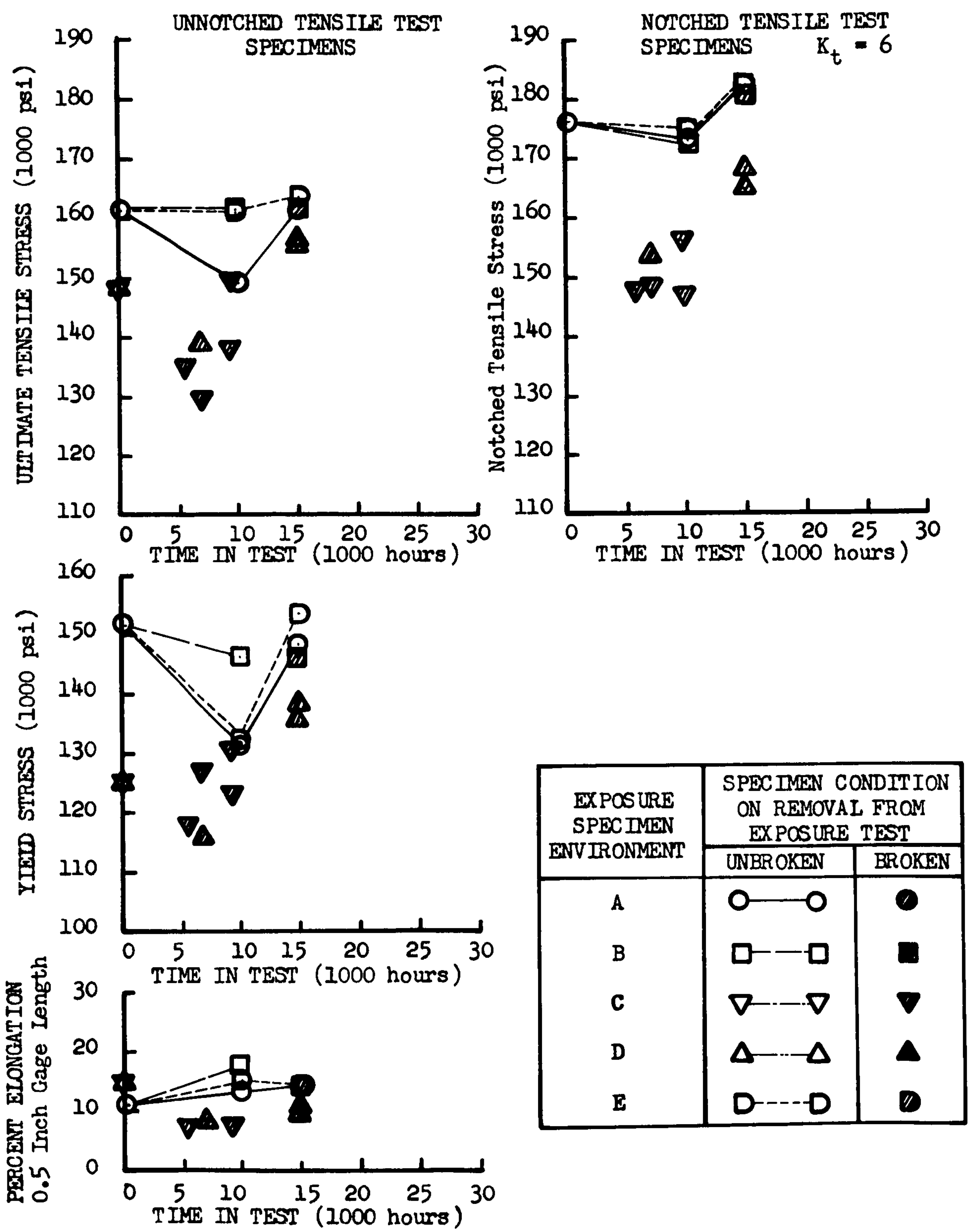


Figure 21.- Titanium 6Al-4V Alloy Stressed Exposure Tensile Test Results.

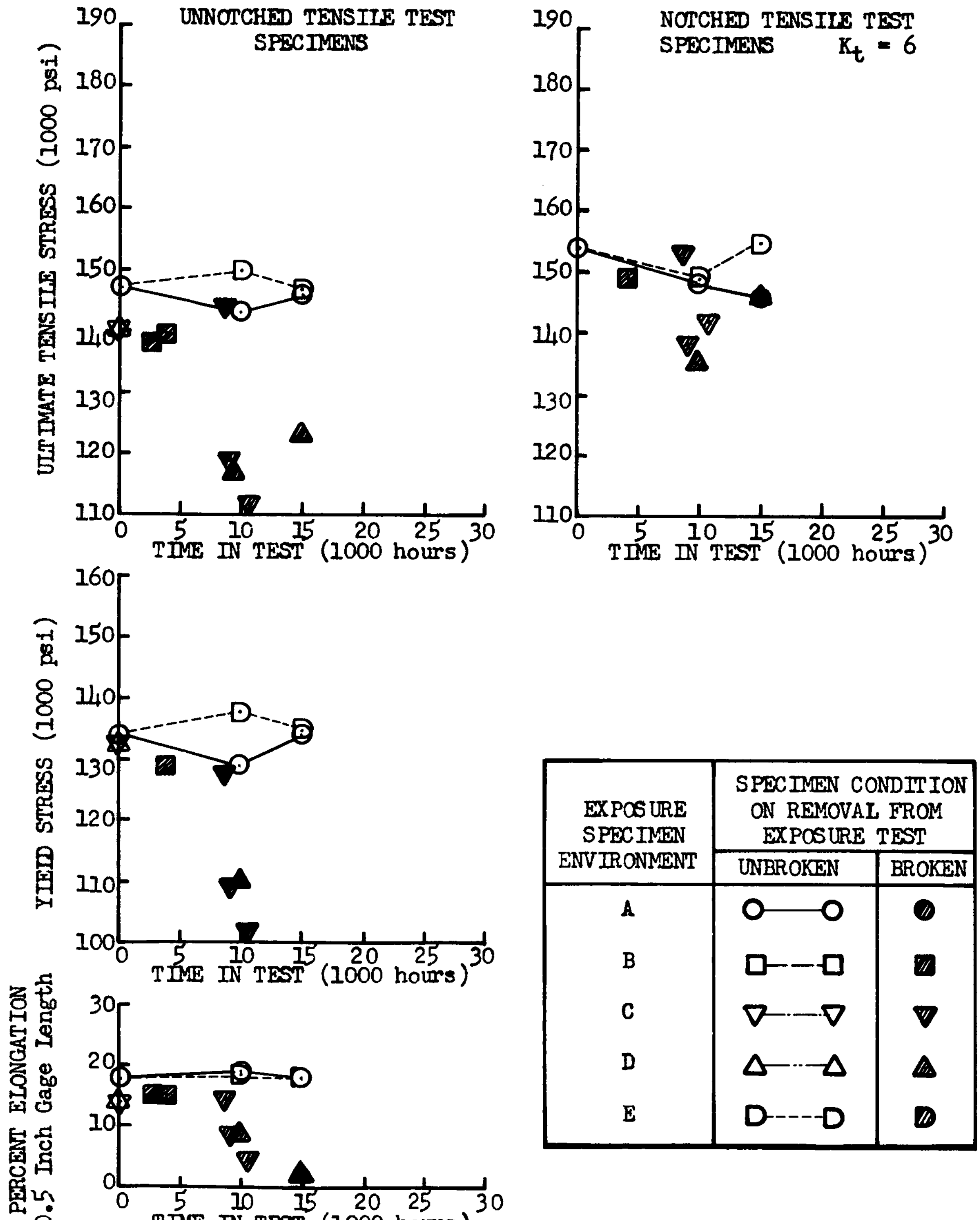


Figure 22.- Titanium 8Al-1Mo-1V Alloy Unstressed Exposure Tensile Test Results.

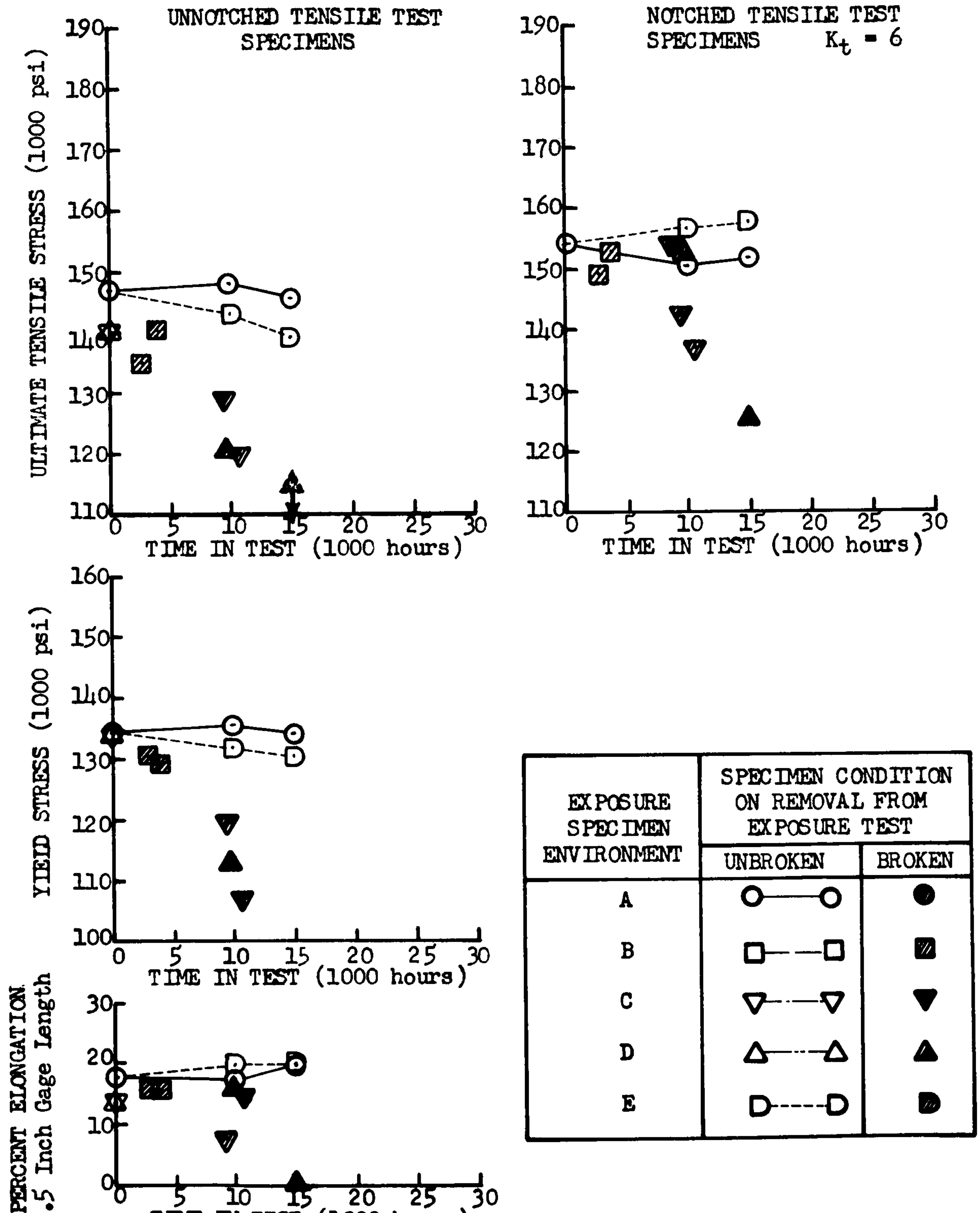


Figure 23.- Titanium 8Al-1Mo-1V Alloy Stressed Exposure Tensile Test Results

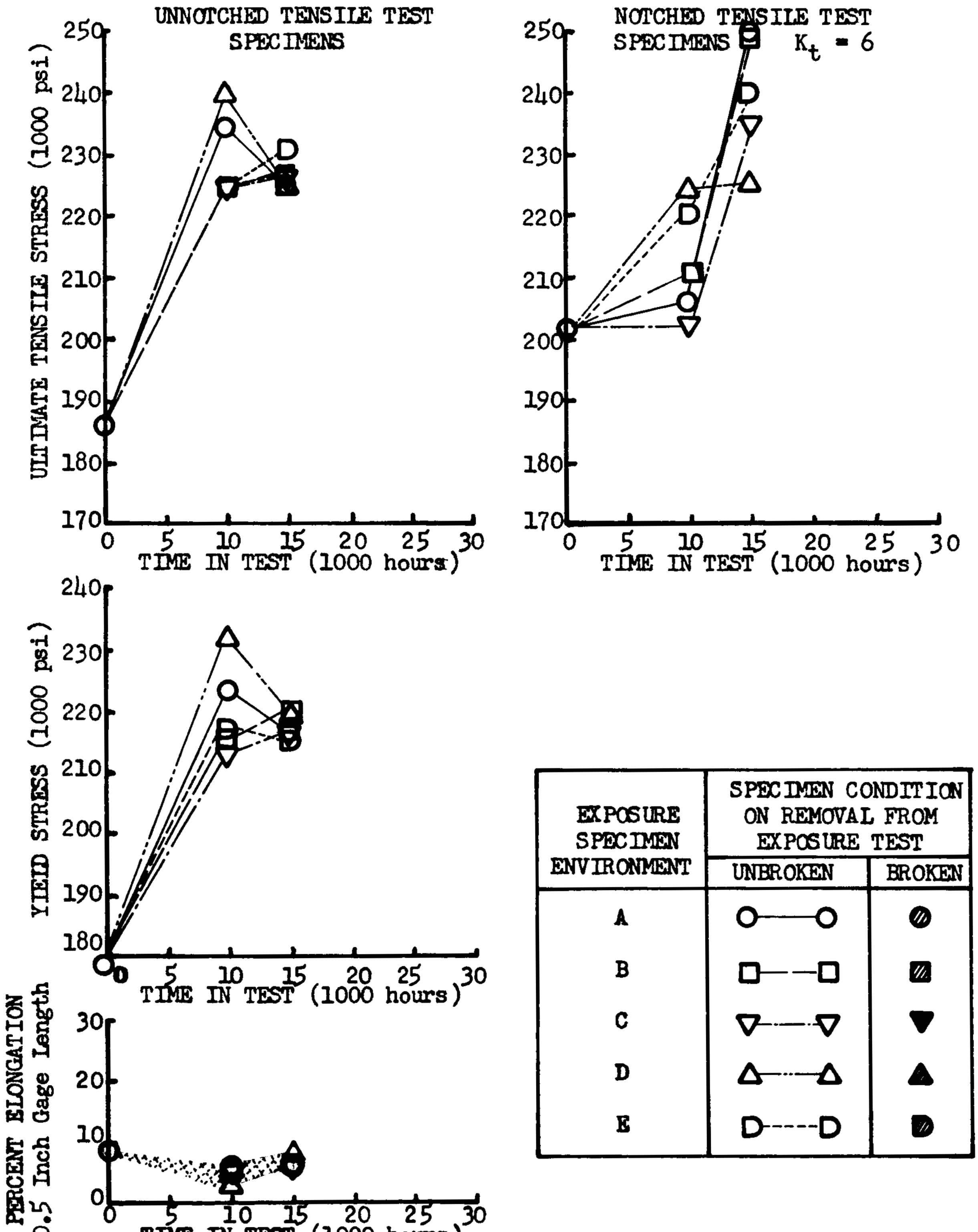


Figure 24.- PH15-7Mo Steel Unstressed Exposure Tensile Test Results.

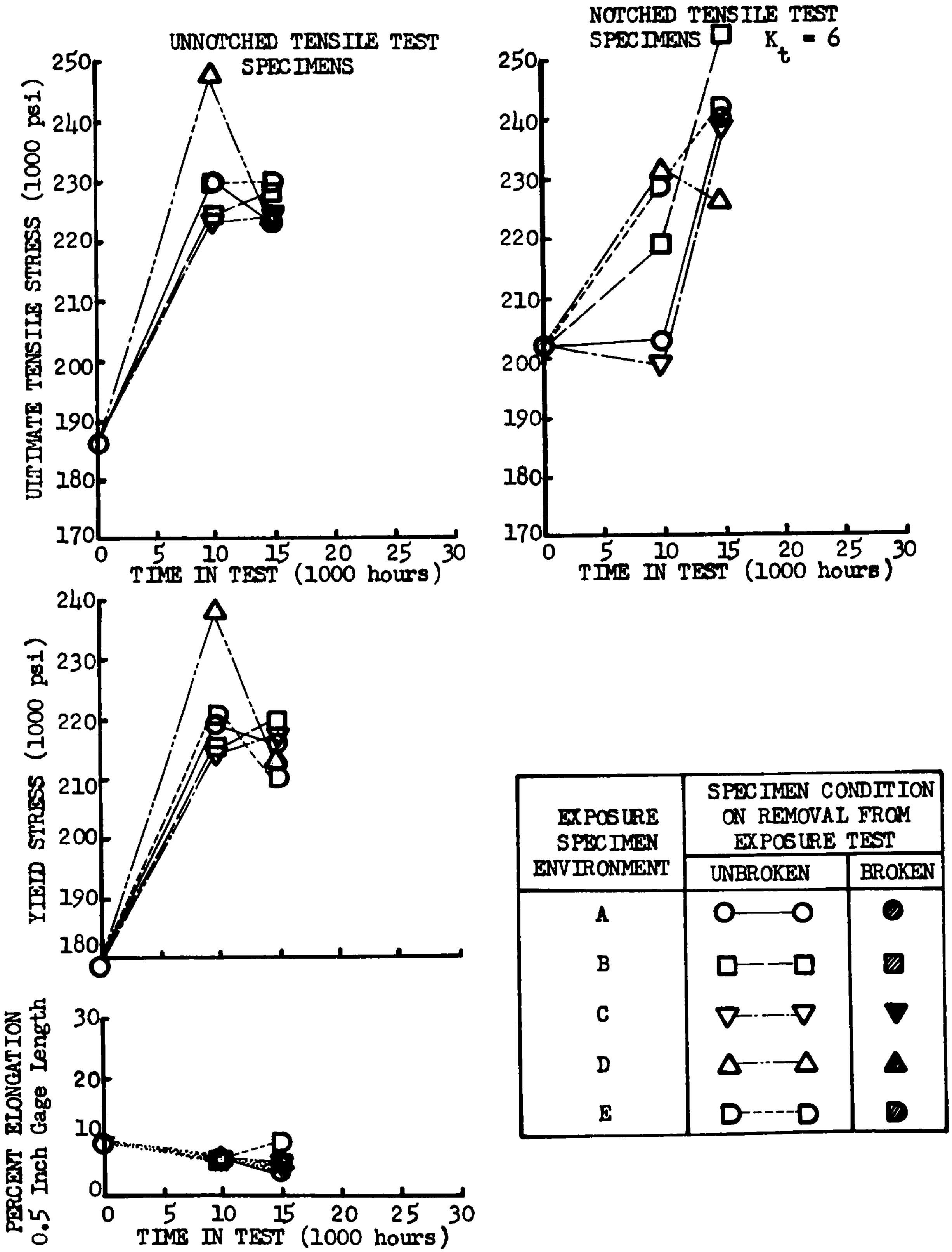


Figure 25.- PH15-7Mo Steel Stressed Exposure Tensile Test Results.

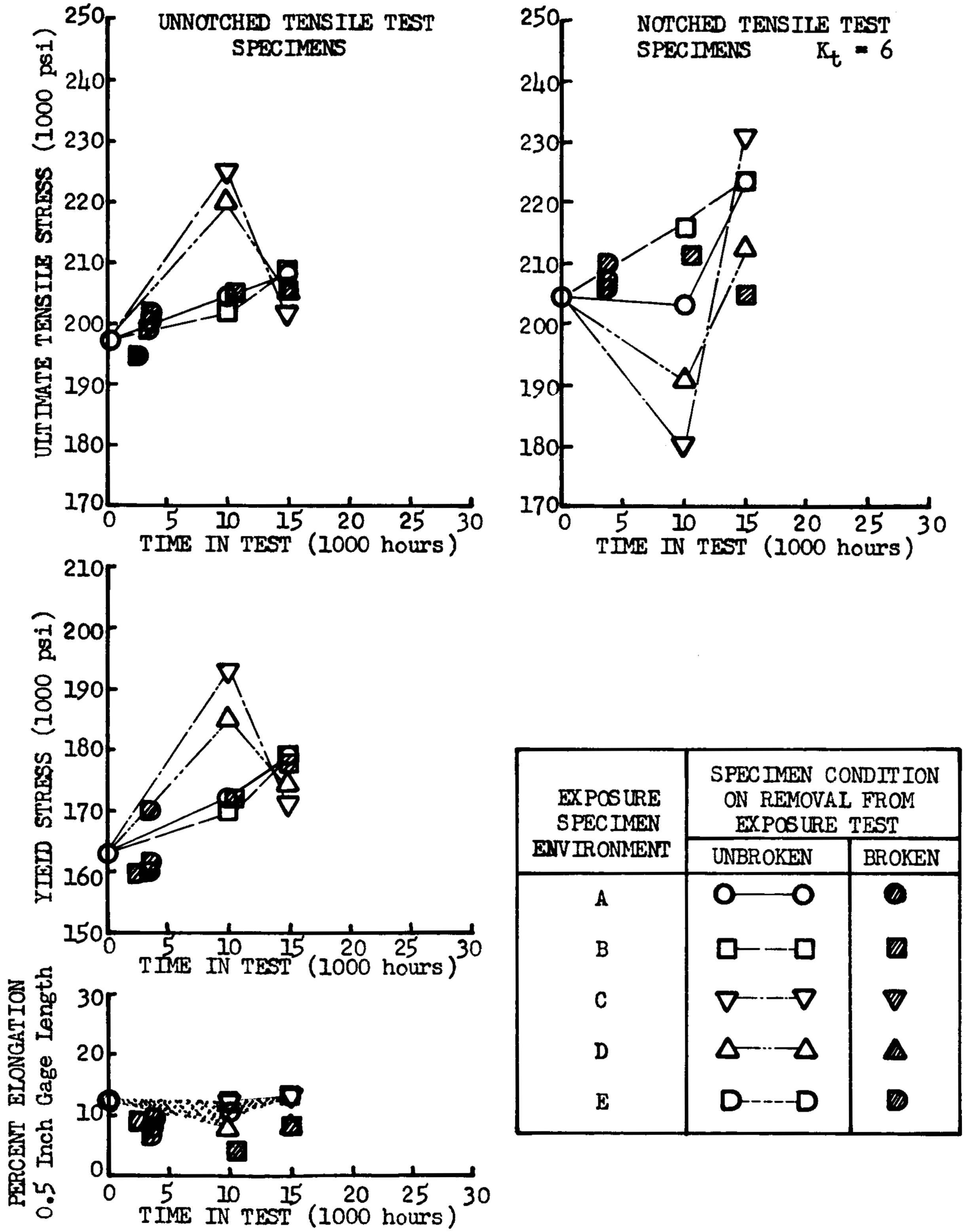


Figure 26.- AM 350 Steel Unstressed Exposure Tensile Test Results.

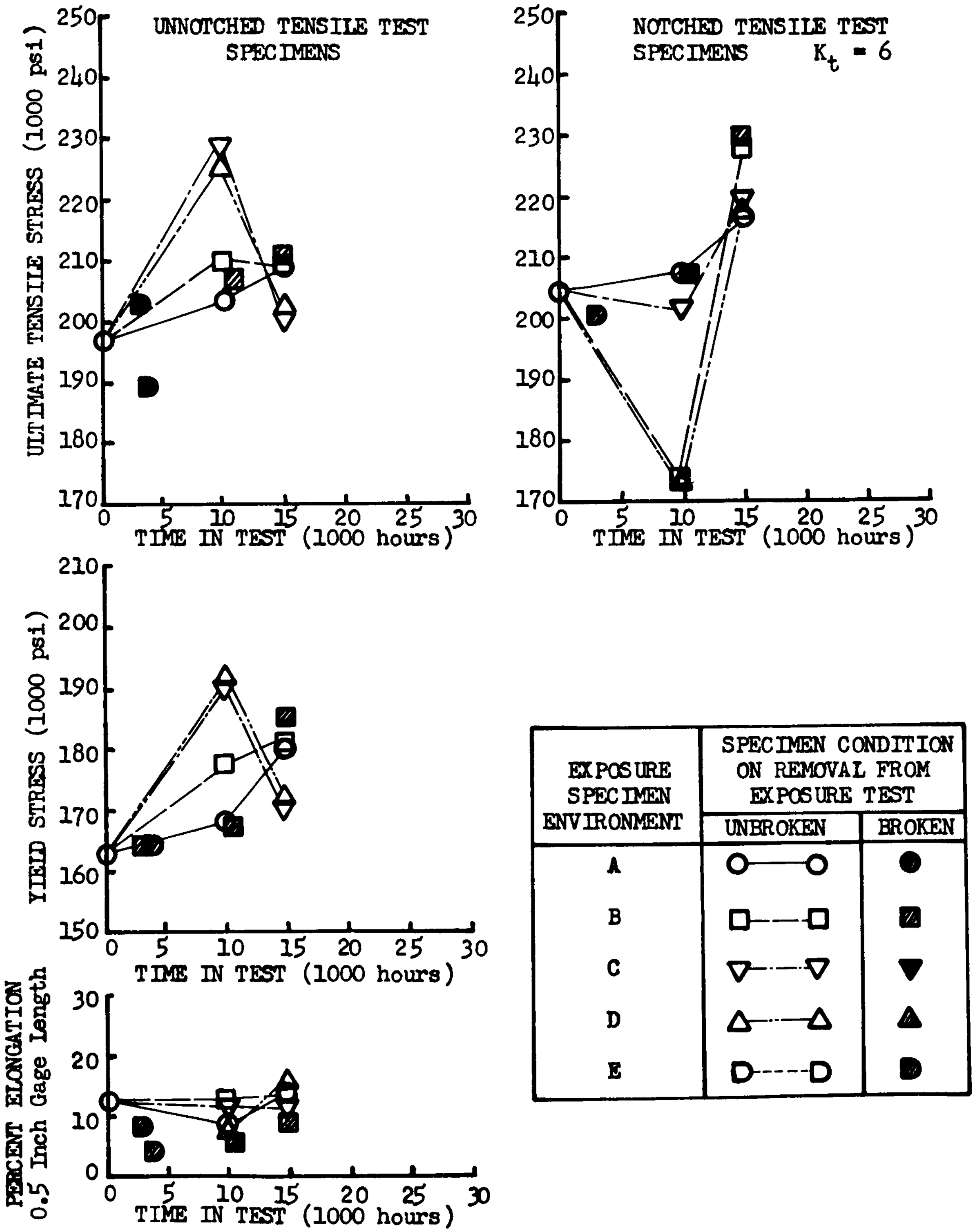


Figure 27.- AM 350 Steel Stressed Exposure Tensile Test Results.

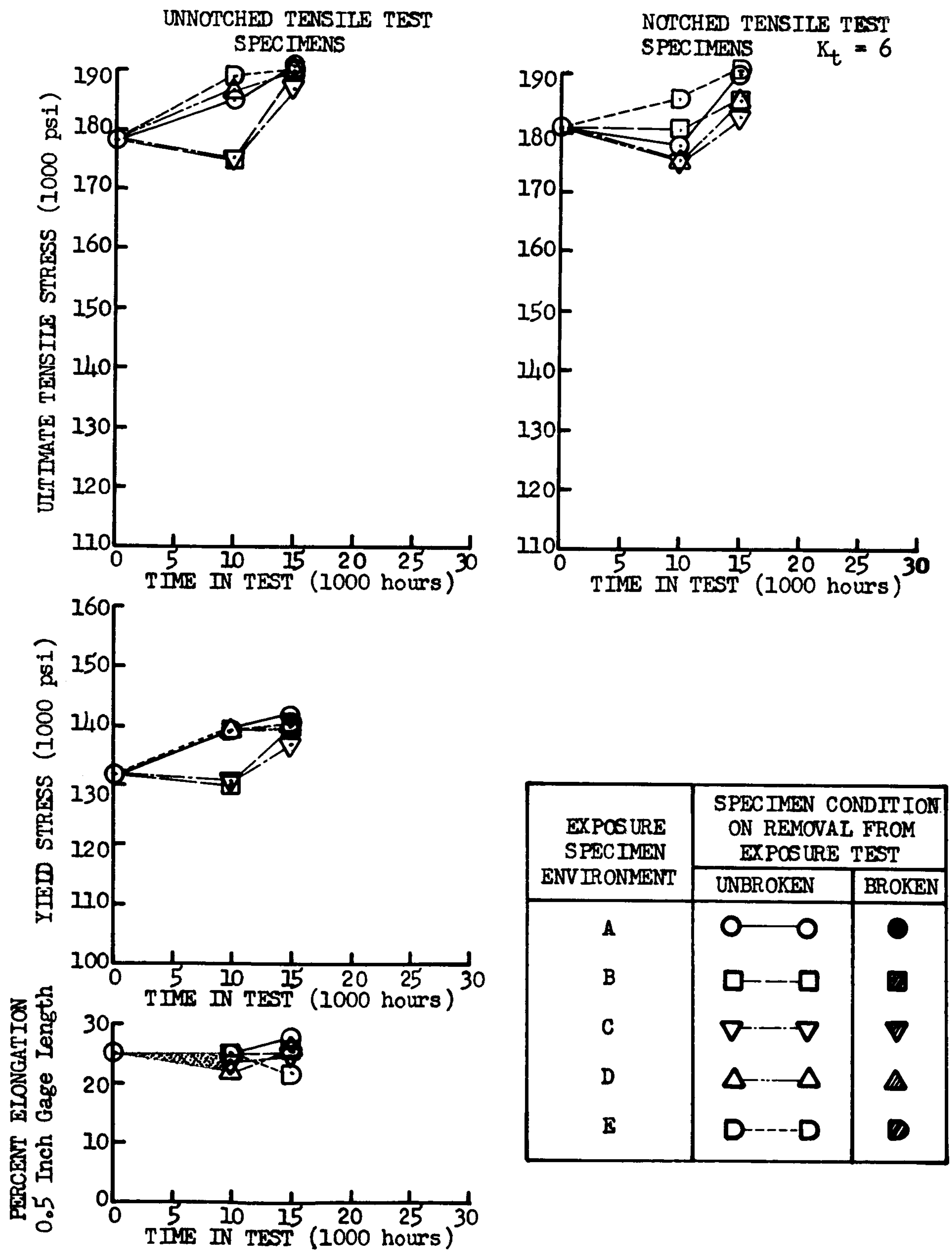


Figure 28.- Inconel 718 Alloy Unstressed Exposure Tensile Test Results.

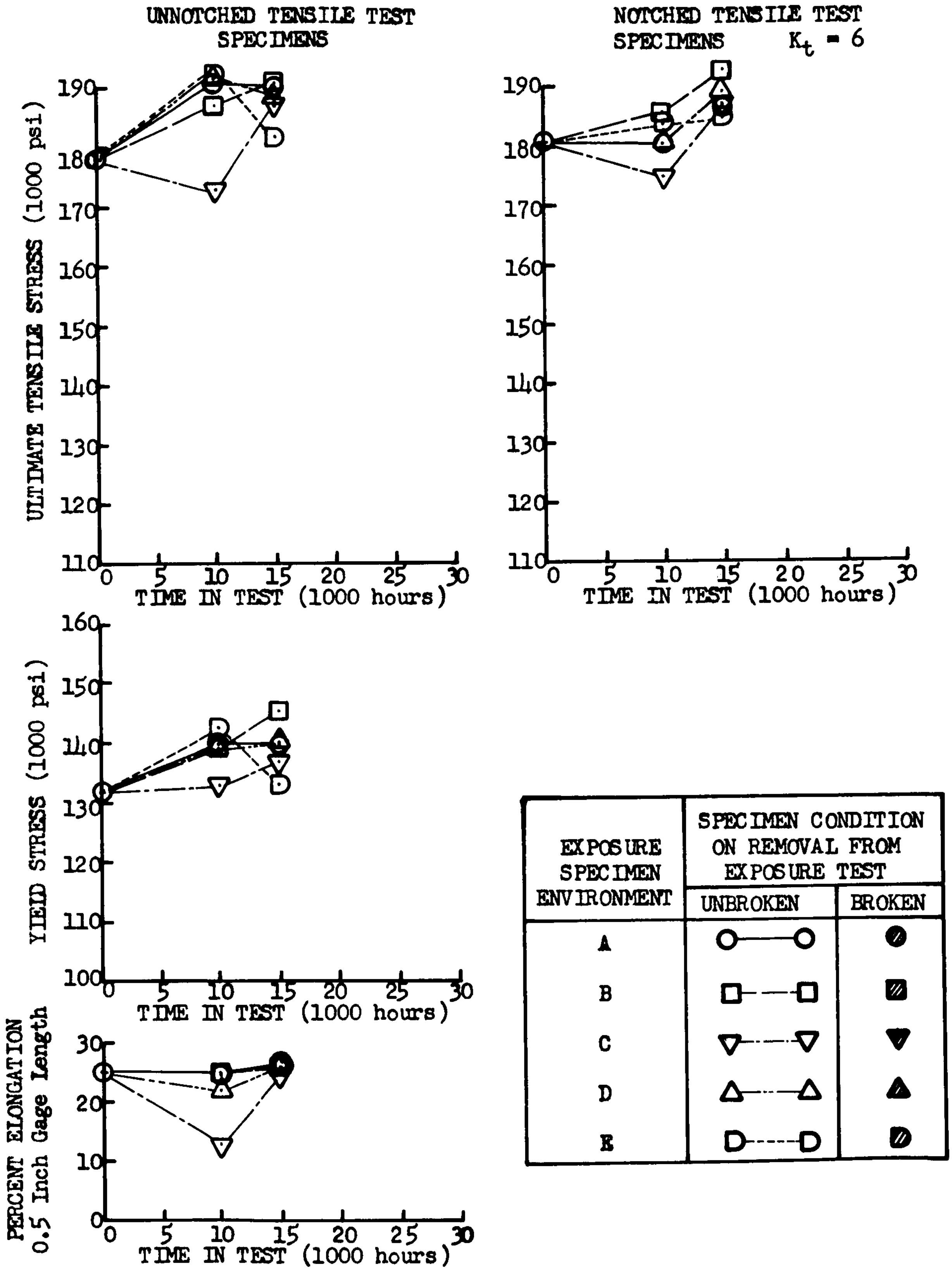


Figure 29.- Inconel 718 Alloy Stressed Exposure Tensile Test Results.

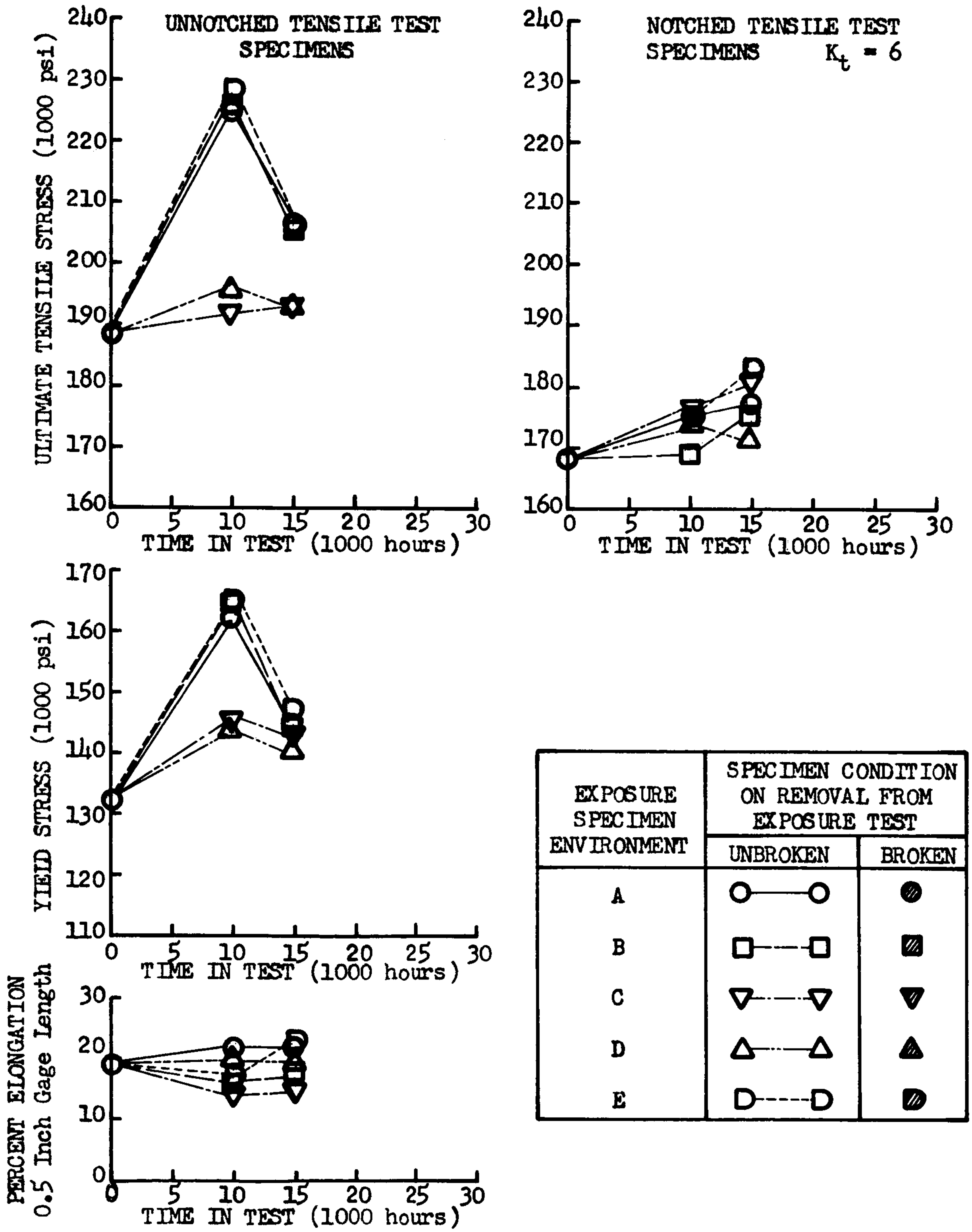


Figure 30.- Rene' 41 Alloy Unstressed Exposure Tensile Test Results.

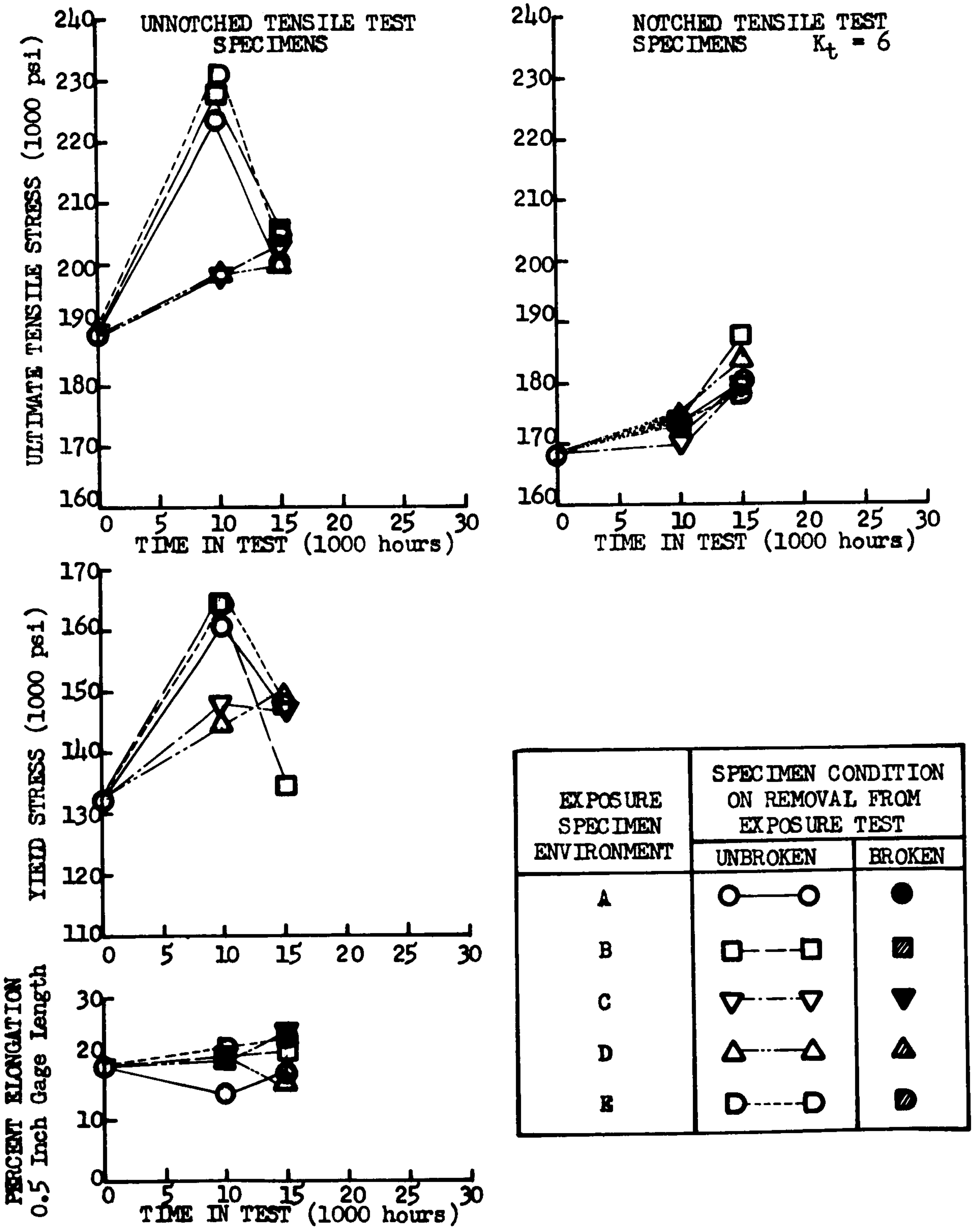


Figure 31.- Rene' 41 Alloy Stressed Exposure Tensile Test Results.

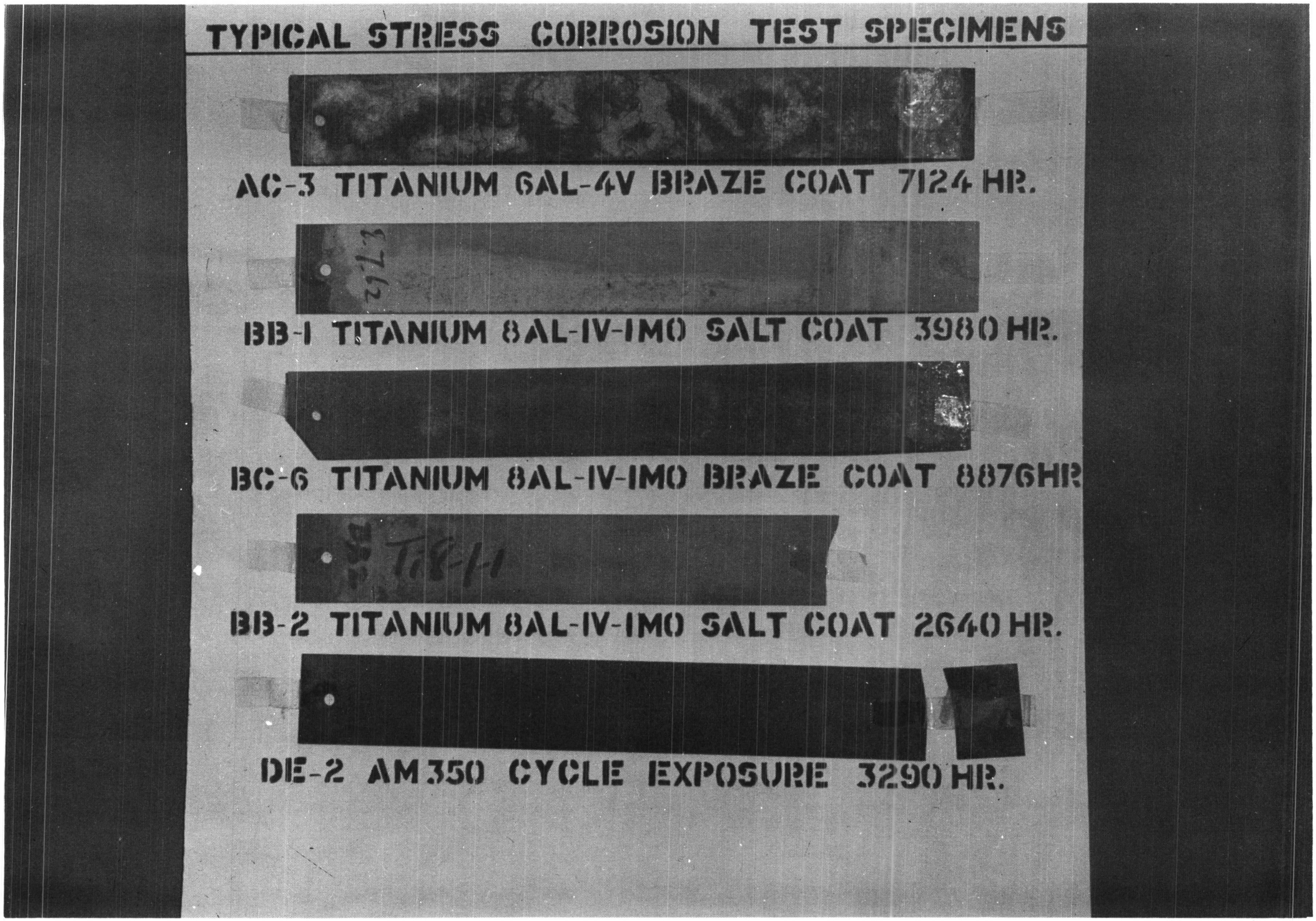
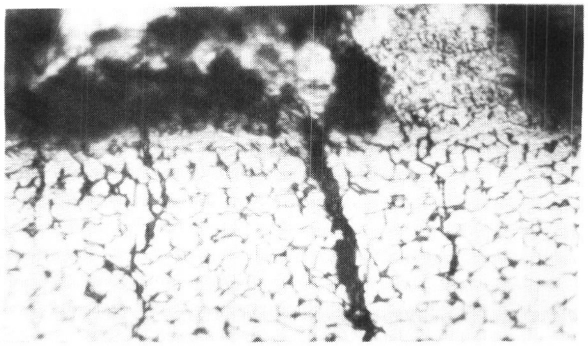


Figure 32 - Examples of Appearance of Exposure Specimens

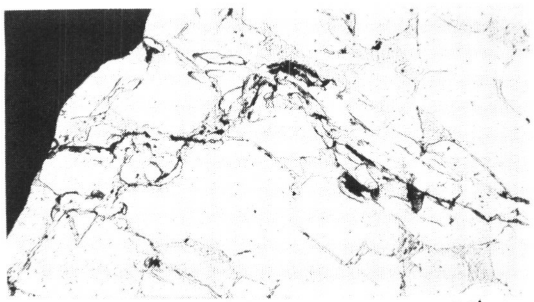
MATERIAL	SURFACE TREATMENT, EXPOSURE	TOTAL SPECIMENS	FAILURE TIME HOURS	SPECIMEN NO.	NOTCHED (N) OR UNNOTCHED (U)
TITANIUM 6Al-4V	BRAZE 650°F	5	5516 7124 9572 9740	AC 6 AC 3 AC 5 AC 2	N U N U
	BRAZE PLUS SALT 650°F	5	15,439 7124 15,480	AD 5 AD 3 AD 2	N U U
TITANIUM 8Al-1V-1 Mo	SALT 650°F	6	2640 3980	BB 2 BB 1	U U
	BRAZE 650°F	5	8876 9308 10,796 13,652	BC 6 BC 2 BC 1 BC 3	N U U U
	BRAZE PLUS SALT 650°F	5	9644	BD 3	U
AM 350 M	SALT 650°F	6	10,796 15,463	DB 5 DB 6	N N
	SALT ALTERNATE 650°F & 100°F	4	2880 3290 3290 3360	DE 4 DE 2 DE 3 DE 1	U U U U

Figure 33 Summary of Stress Corrosion Failures

7,124 HOUR EXPOSURE
FAILED



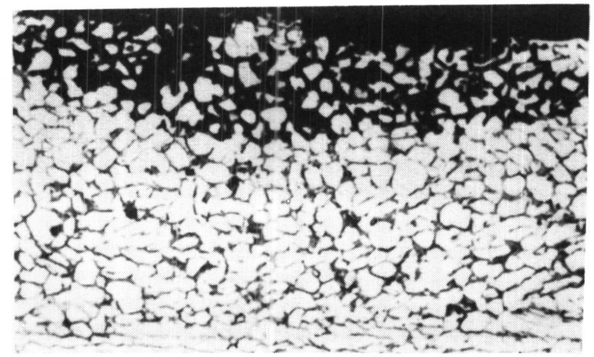
Etched x 500



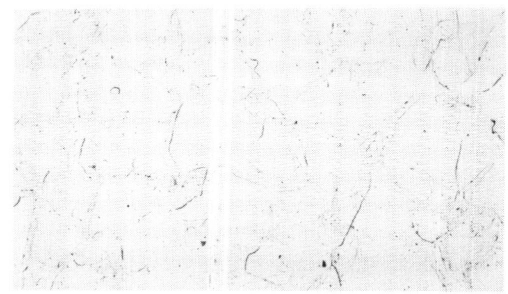
Two stage replica x 2500

Two stage replica x 15,000

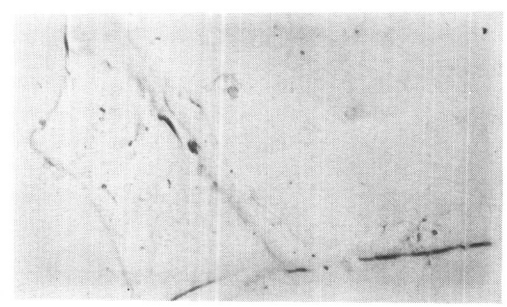
15,000 HOUR EXPOSURE
FAILED



Etched x 500

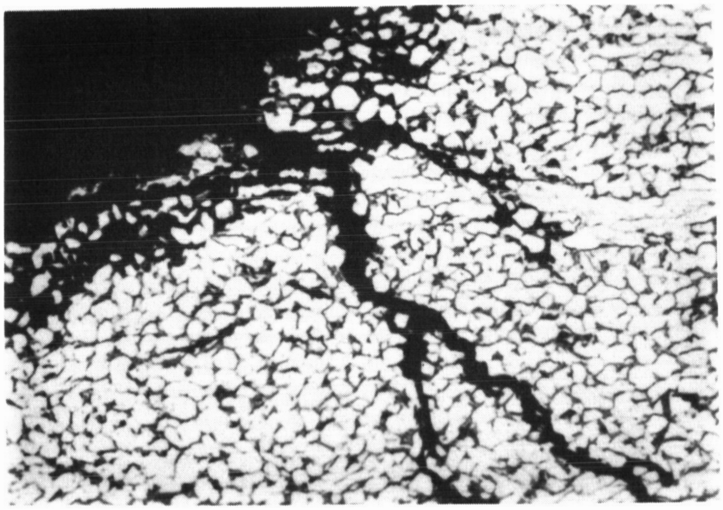


Two stage replica x 2500



Two stage replica x 15,000

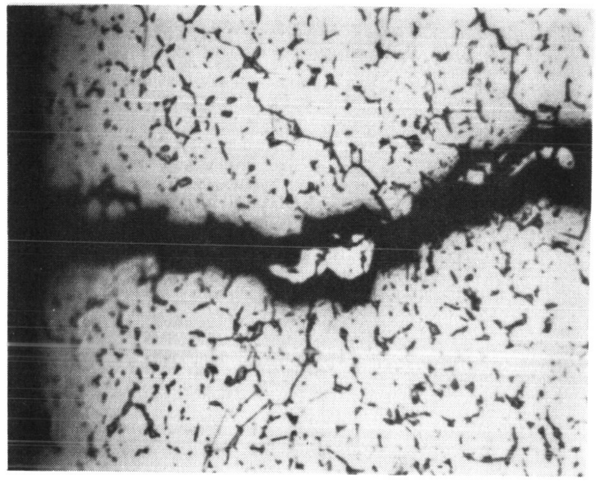
Figure 34.- Microstructure of Braze and Salt Coated Titanium 6Al-4V Alloy after exposure in circulating air at 650°F. (Specimens AD3 and AD5)



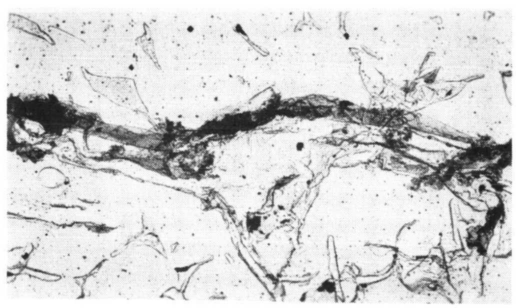
Etched x 500

Figure 35.- Microstructure of Braze and Salt Coated Titanium 6Al-4V Alloy notch specimen AD5 showing surface crack. Specimen failed after 15,000 hours exposure in circulating air at 650°F.

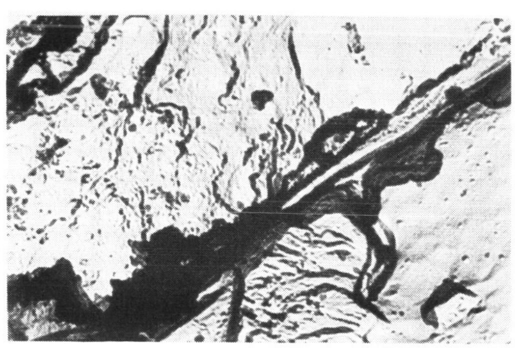
9,308 HOUR EXPOSURE
FAILED



Etched x 500



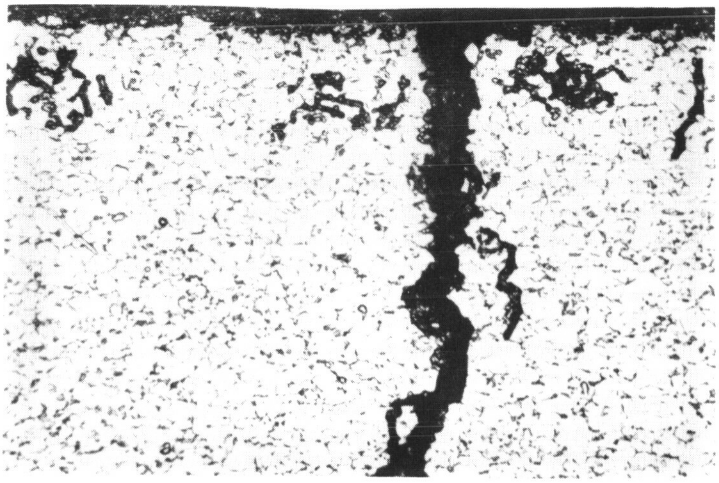
Two stage replica x 2500



Two stage replica x 15,000

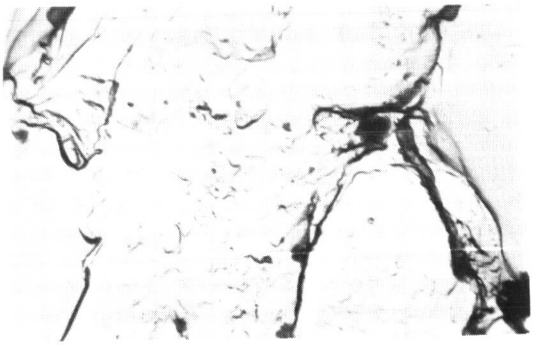
Figure 36 .- Microstructure of Braze Coated Titanium 8Al-1Mo-1V Alloy after exposure in circulating air at 650°F. (Specimen BC2)

9,644 HOUR EXPOSURE
FAILED



Etched x 500

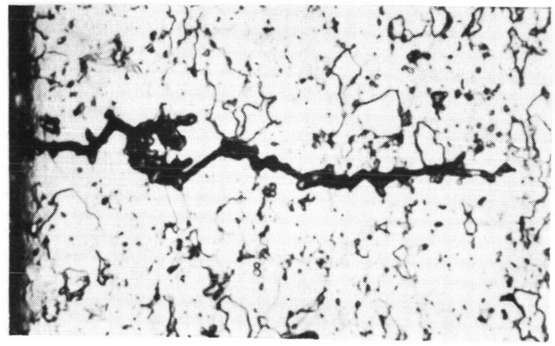
Two stage replica x 2500



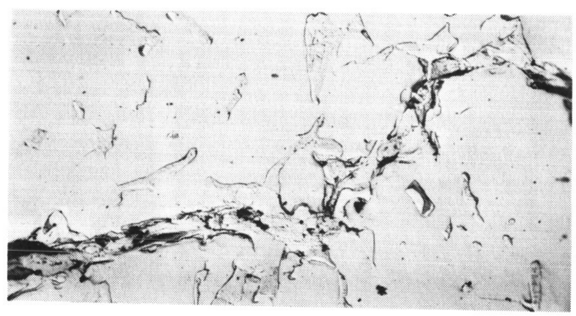
Two stage replica x 15,000

Figure 37.- Microstructure of Braze and Salt Coated Titanium 8Al-1Mo-1V Alloy after exposure in circulating air at 650°F. (Specimen BD3)

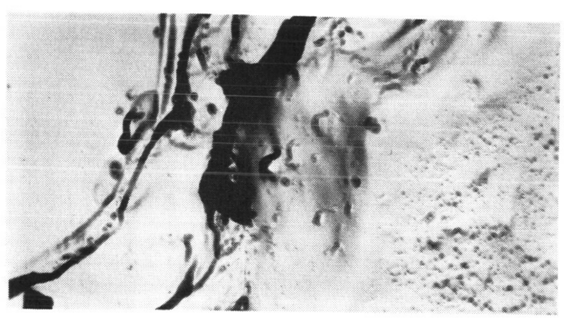
3,980 HOUR EXPOSURE
FAILED



Etched x 500



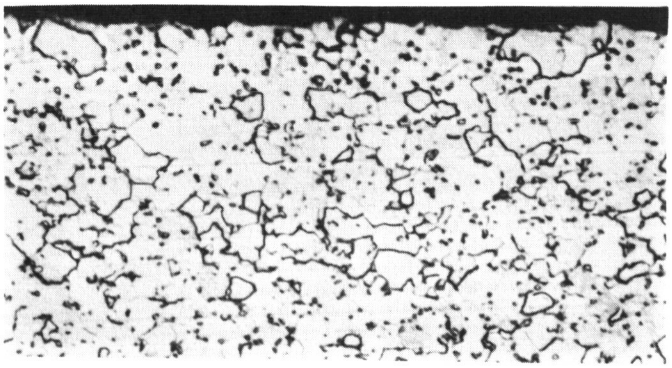
Two stage replica x 2500



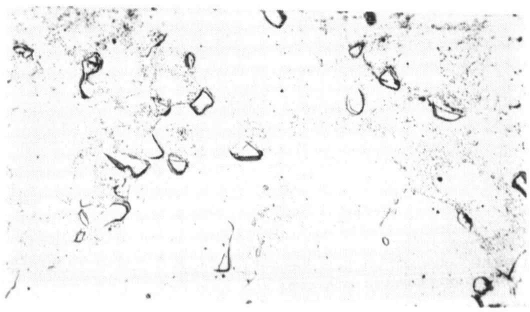
Two stage replica x 15,000

Figure 38.- Microstructure of Salt Coated Titanium 8Al-1Mo-1V Alloy after exposure in circulating air at 650°F. (Specimen BB1)

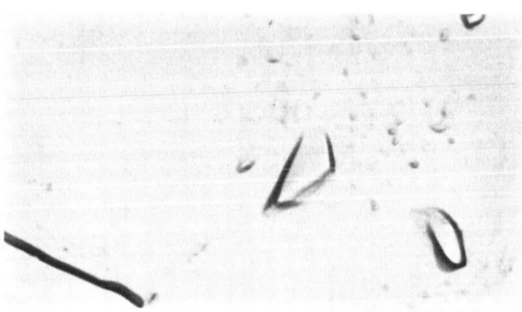
10,000 HOUR EXPOSURE
NO FAILURE



Etched x 500

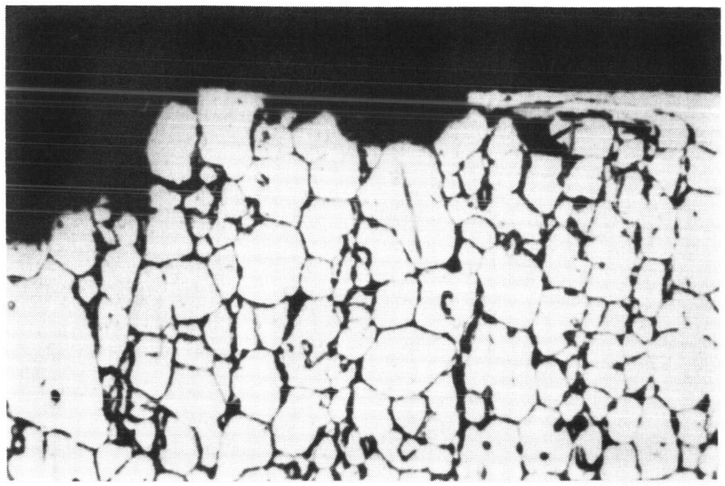


Two stage replica x 2500



Two stage replica x 15,000

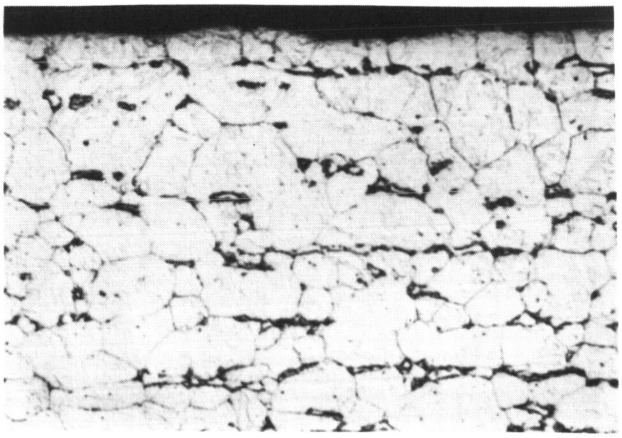
Figure 39.- Microstructure of Salt Coated Titanium 8Al-1Mo-1V Alloy after alternating 14 day exposure in circulating air at 650°F and in humidity cabinet at 100°F. (Specimen BE1)



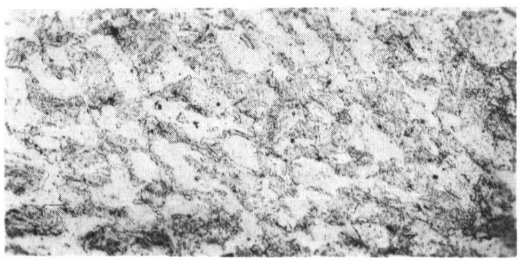
Etched x 500

Figure 40 .- Microstructure of Salt Coated AM 350 M Steel notch specimen DB6 at fracture in notch showing old and new crack areas. Specimen failed after 15,000 hours exposure in circulating air at 650°F.

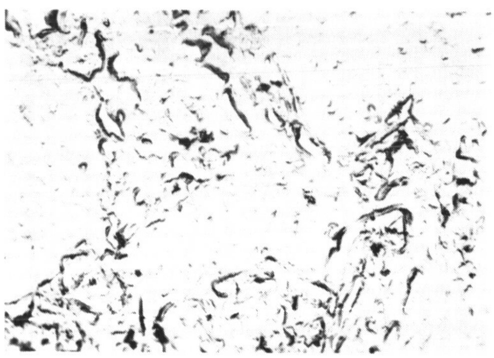
10,796 HOUR EXPOSURE
FAILED



Etched x 500



Two stage replica x 2500



Two stage replica x 15,000

Figure 41.- Microstructure of Salt Coated AM 350 M Steel after exposure in circulating air at 650°F. (Specimen DB5)

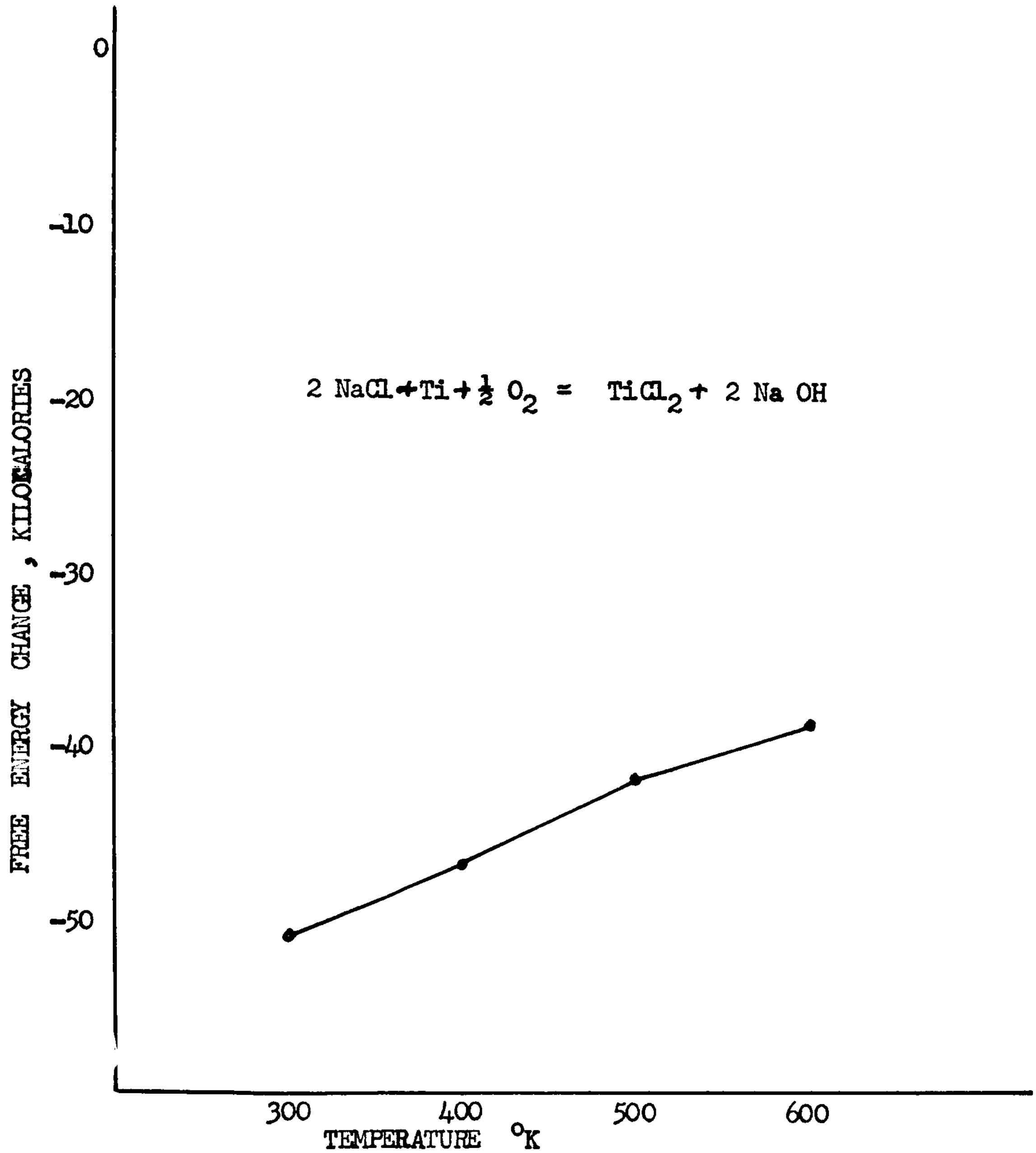
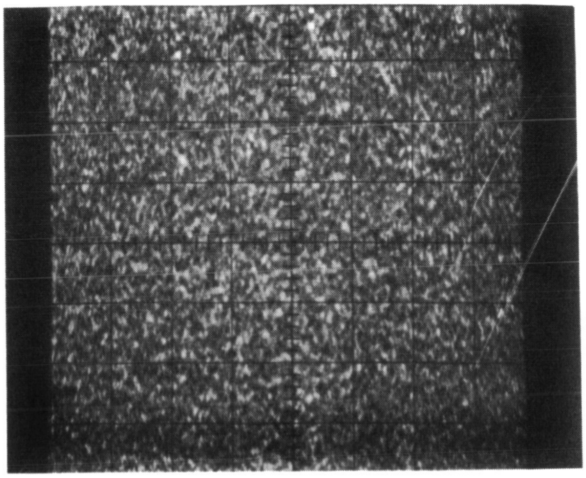
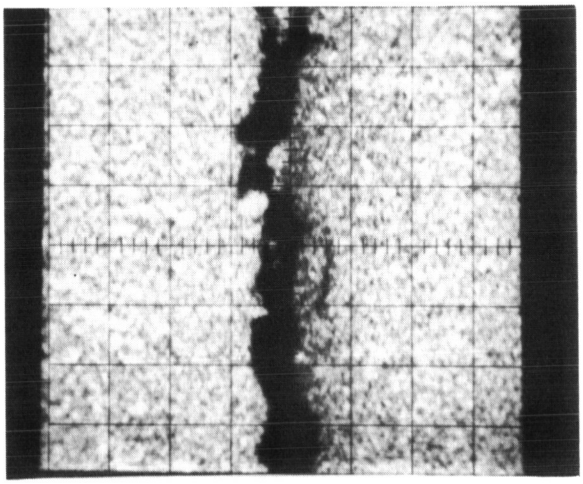


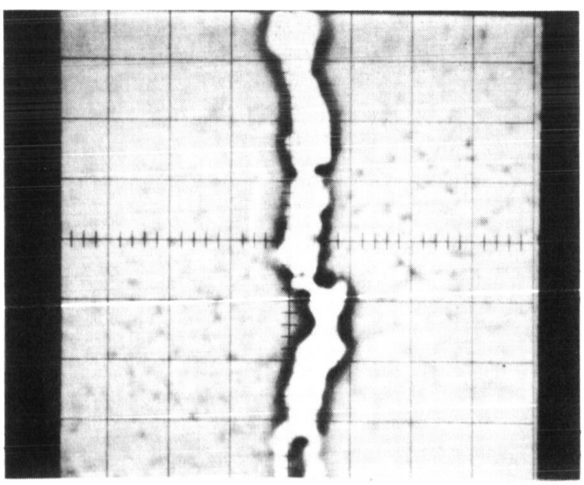
Figure 42; Change in Free Energy of a possible Stress Corrosion Reaction.



Backscatter Image
X 888
Unexposed Alloy

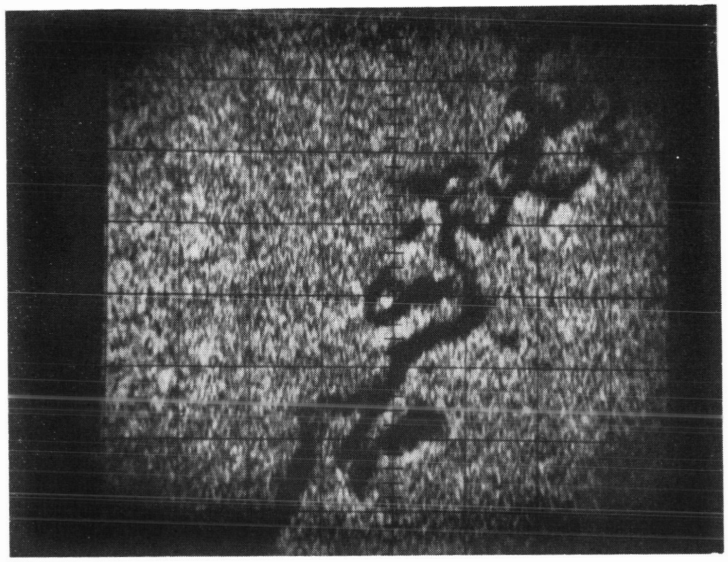


Backscatter Image
X 888
Salt Coated Specimen
BB1K
Failure Time 3980 Hours

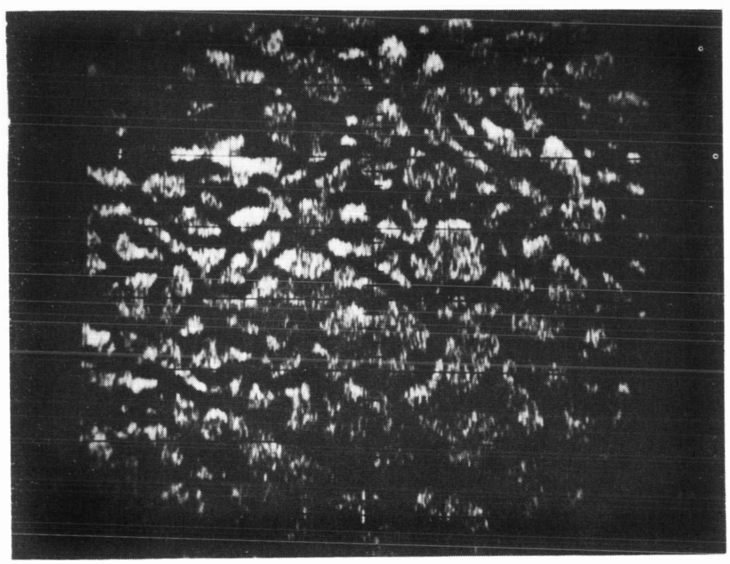


Sample Current Image
X 888
Specimen as above

Figure 43 Electron Microprobe Analysis of Titanium 8-1-1 Alloy



Small Crack near Large Crack
Back-scatter Image x 888
AD3K



Network near Sample Edge
Back-scatter Image x 888
AD3K

Figure 44: Electron Microprobe Analysis of Titanium 6Al-4V

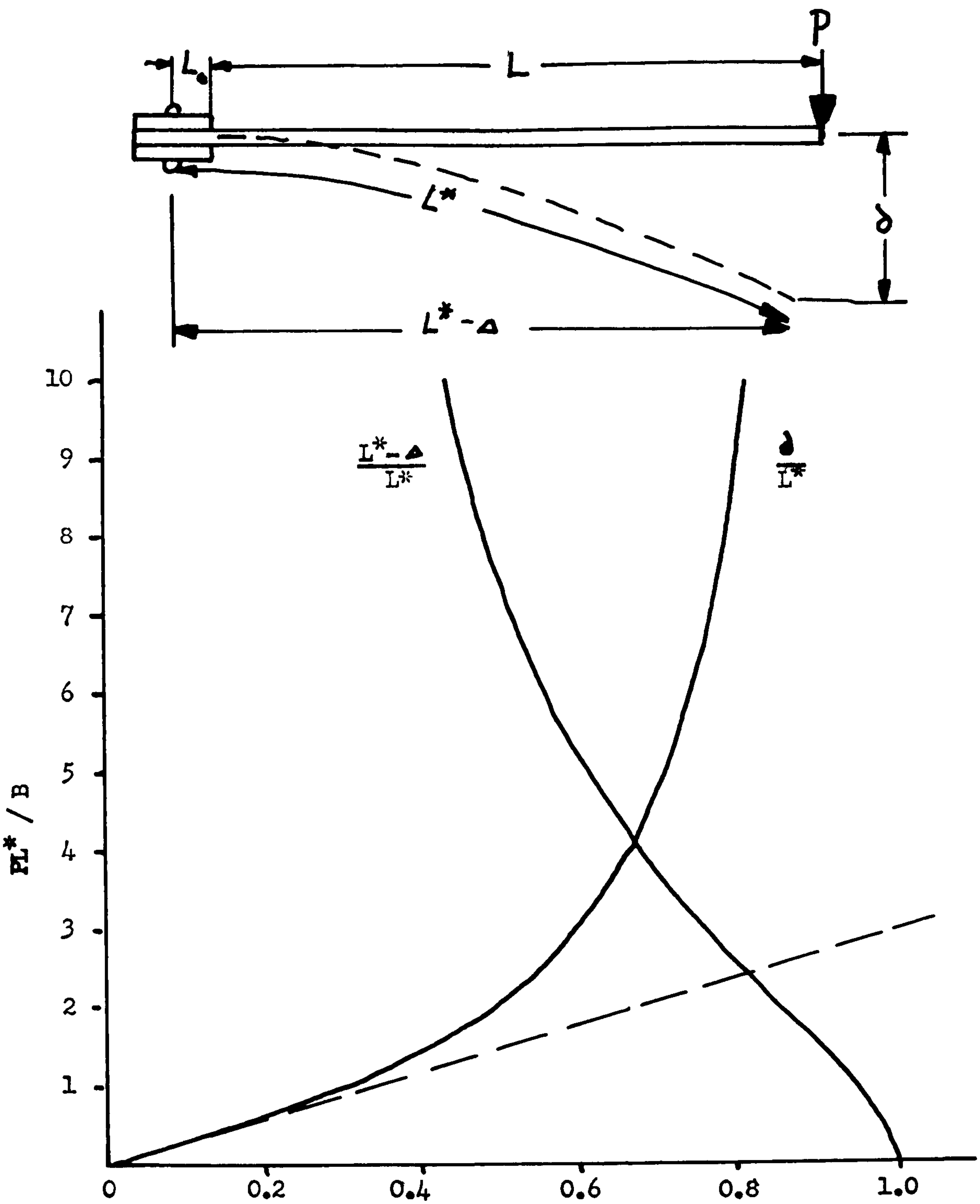


Figure 45 Deflection and Moment Arm versus Load - Stiffness Parameters

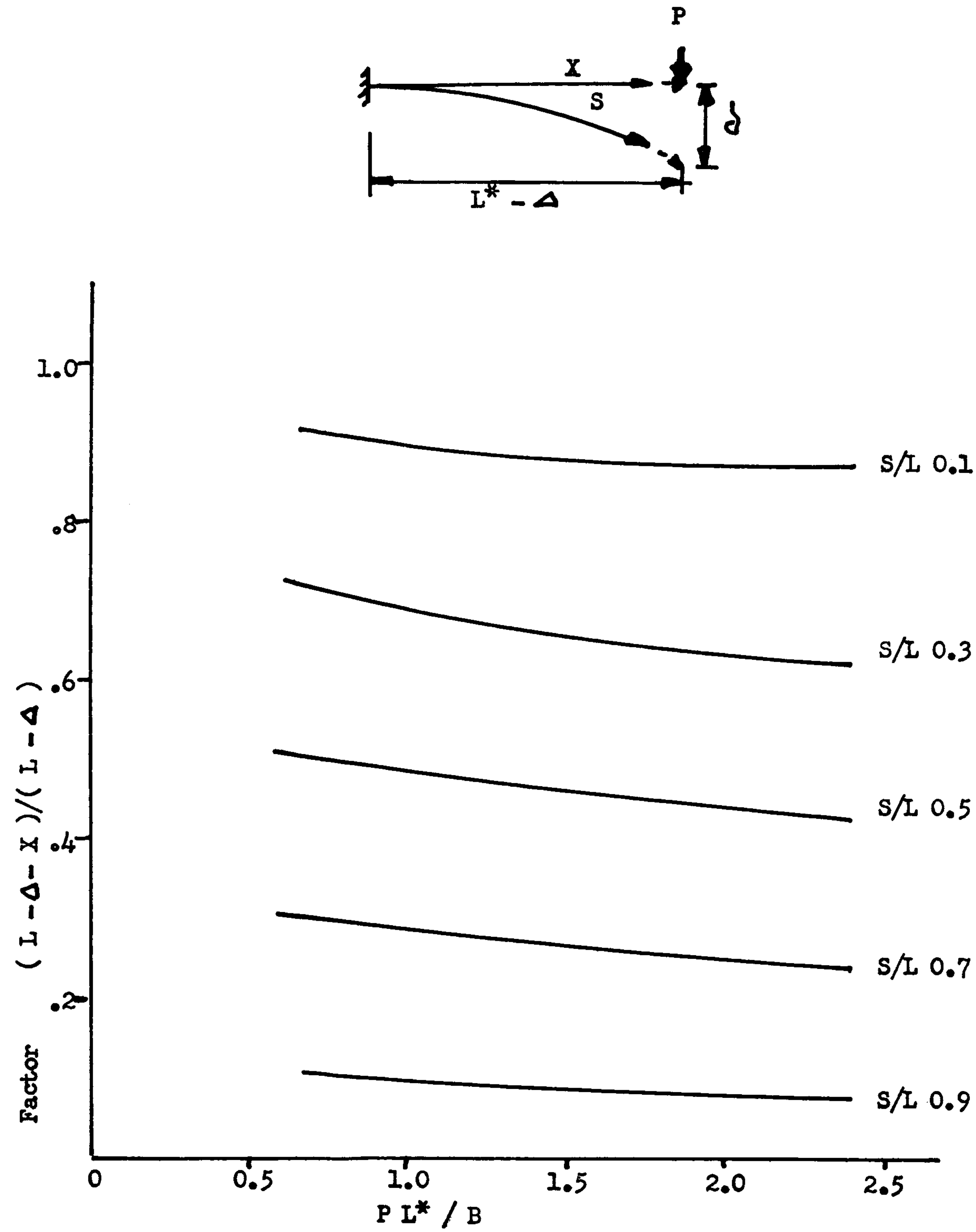


Figure 46 ; Moment Coefficients versus Load - Stiffness Parameters for intermediate Beam Locations.

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July, 1964, North American Aviation, Inc.,
Los Angeles Division, Los Angeles, Calif.